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Environmental Modelling & Software 19 (2004) 219–234

Environmental Modelling & Software

www.elsevier.com/locate/envsoft

An overview of model integration for environmental applications—components, frameworks and semantics

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Received 4 November 2002; received in revised form 8 April 2003; accepted 14 April 2003

Abstract

In recent years, pressure has increased on environmental scientist/modellers to both undertake good science in an efficient and timely manner, under increasing resource constraints, and also to ensure that the science being performed is immediately relevant to a particular environmental management context. At the same time, environmental management is changing, with increasing requirements for multi-scale and multi-objective assessment and decision making that considers economic and social systems, as well as the ecosystem. Integration of management activities, and also of the modelling undertaken to support management, has become a high priority. To solve the problems of application and integration, knowledge encapsulation in models is being undertaken in a way that both meets the needs for good science, and also provides the conceptual and technical structures required for broader and more integrated application of that knowledge by managers. To support this modelling, tools and technologies from computer science and software engineering are being transferred to applied environmental science fields, and a range of new modelling and software development approaches are being pursued. The papers in this Special Issue provide examples of the integrated modelling concepts and applications that have been, or are being, developed. These include the use of object-oriented concepts, component-based modelling techniques and modelling frameworks, as well as the emerging use of integrated modelling platforms and metadata support for modelling semantics. This paper provides an overview of the science and management imperatives underlying recent developments, discusses the technological and conceptual developments that have taken place, and highlights some of the semantic, operational and process requirements that need to be addressed now that the technological aspects of integrated modelling are well advanced.

Keywords: Model integration; Component-based modelling; Modelling frameworks

1. Introduction

Integration has become a common concept in environmental management in recent years. Policies and management philosophies such as integrated resource management and integrated environmental management abound, and for land and water management activities the focus is often on integrated catchment (watershed) management (ICM). In Australia, ICM has been widely adopted into policy (Mitchell and Hollick, 1993), requiring that management of our land, vegetation and water systems be undertaken in a way that considers the interconnected nature of these systems, and their interrelationships with our social and economic systems and the ecosystem. This so-called triple bottom line of economics, society and ecosystem is a thread that runs through environmental management worldwide, albeit with varying degrees of legislation and commitment of government and society. To support this integrated approach, there is a need for better modelling tools to help represent, understand and explore natural systems. Associated with development of new modelling tools, has come a greater requirement for flexibility, so that knowledge gained in development of a certain solution is not lost when transported to another site, or time, or policy.

Turning the concept of integration into knowledge and actions has spawned a considerable research and modelling effort. These efforts have not only covered discipline-specific areas such as biology, geology and

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1364-8152/$ - see front matter
doi:10.1016/S1364-8152(03)00150-6

hydrology, but have extended into consideration and representation of trans-disciplinary systems, from point to planetary scale. The area of integrated assessment related to climate change is an example of this, where the affects of future climate on social, economic and ecosystems are investigated (Dowlatabadi, 1995; Weyant et al., 1995; Parker et al., 2002). Integrated assessment and the more general area of integrated environmental management have, over the last 10 years, become drivers for development of new and different modelling tools, concepts and approaches. For many researchers in environmental areas, who may previously have focussed on the flow of water or the movement of air in isolation from external system influences, these changes have meant a broadening of possible research applications, as research produced by one scientist may be picked up by others and linked with other models to answer a question that was not even thought of in the initial development. Of course, many scientists have held the broader view of application of their science for years, but this broader consideration is now becoming more often a requirement than an inclination.

Another aspect affecting the role and practice of scientists working in environmental fields is the increasing influence and prevalence of Mode 2 science—that is science in the context of application rather than the context of discipline (Gibbons et al., 1994). Environmental researchers are being increasingly encouraged to make their science ‘relevant’ to the extent that many scientists now take account of the application context of science from the initial analysis phases of scientific endeavour. Given movement in the balance of scientific effort towards application and exploration, and tighter economic constraints on science, another aspect related to modelling has come to the fore—that of less time available for developing computer modelling based solutions. We must therefore be more efficient about the way we apply science through modelling, so as to leave sufficient time to do science!

Thus, the needs of users of science, the problems being addressed by science and the way that we do science are all driving developments in concepts and methods, and the modelling that supports these. Key amongst these developments, and strongly influenced by the needs of today’s scientists, is ‘integrated’ modelling, whereby different components of the natural and other systems are modelled in a linked way, ideally with representation of feedbacks, loops, responses, thresholds and other features of system behaviour. Traditional modelling approaches have only occasionally included these considerations, and there are certainly no modelling methods currently operating across disciplines that offer the tools required by Mode 2 science and the needs of integrated environmental management applications.

Modelling solutions arising from the computer science and software engineering disciplines, as well as the commercial sector, offer promise in this area. These tools, in conjunction with changes to development and adoption processes by scientists and managers, are offering new ways that suit both the needs of application science and problem situations commonly encountered.

This paper considers the problems we are facing in development and application of our science in the context of environmental management, examines the leaps forward that have taken place over the last 5 years with the movement of knowledge from computer science and software engineering to applied environmental science fields, and discusses some of the modelling and software development approaches that are currently being pursued to deliver the tools and capabilities desired by environmental managers. These tools and techniques include existing use of object-oriented concepts, component-based modelling techniques and modelling frameworks, as well as emerging use of integrated modelling platforms and metadata support for modelling semantics. Companion papers (Krivtsov et al., this issue; Lam et al., this issue; Pullar, this issue; Quinn et al., this issue; Rahman et al., this issue; Voinov et al., this issue; Watson and Rahman, this issue) provide both context for this work and also examples of the concepts and applications that have been, or are being, developed.

2. Environmental management and modelling requirements

Environmental modelling is undertaken for a vast range of reasons, although fundamental to these is normally the desire to investigate, understand and represent some natural phenomenon. In the context of integrated environmental management, such modelling includes not only air, land, water, animal and plant, and the interactions and fluxes between these, but also the interactions of these with non-natural systems that includes constructed infrastructure, economics and social systems.

At the core of most environmental modelling applications is the desire to represent natural processes for purposes that include:

- understanding of the processes,
- testing of the representation of processes,
- development of questions or data needs to allow better representation,
- providing answers to specific questions about the likely future state of an environmental system, and
- support for investigation of alternative future states under alternative management interventions.

Further to these application aspects, increases in the use of participatory approaches to management over the last 10 years have resulted in demand for both new modelling tools and new development and delivery mechanisms. Such processes require flexible tools that allow models to be constructed rapidly and openly, and flexible interfaces that allow differently modelled parts of the system to work together, so that investigation of a management action or policy option can include consideration of not only directly affected parts of the system, but also extended effects, such as flow-on and secondary consequences. The use of flexible participative modelling approaches have existed in environmental management modelling for over 20 years (Holling, 1978; Walters, 1986) but only in the last decade or less have changes in institutional arrangements and technical support allowed these to enter the mainstream (Costanza and Ruth, 1998; Vennix, 1999).

With this background of management, institutional and scientific process changes, it can be seen that there is a range of roles for modelling that extends well beyond just the representation of natural phenomena. In contrast to these changes, it can be argued that the development of models, which mostly arise from scientific investigation of phenomena, is still largely being undertaken in an entrenched linear process that gives little thought during development to the problems of model integration that may arise in the later life of a model. This process of model development and application passes through some or all of four possible levels, as follows:

- The base level (Level I) of development is by a researcher developing a model for specific research purposes, often based on a particular problem at a particular scale or site. The potential users of the model are generally thought of as the developer and colleagues in the same field. Colleagues in other fields who wish to gain an understanding of some particular function that affects their science, can also be considered as primary users of this model. Communication of models at this level is most often done through conference and journal publications.
- At the next level (Level II), these research-focussed models have been found to have some general utility, and have been tested and found to be applicable to a range of problems at various sites or scales. These models then become examples of a particular style or conceptual approach, and are re-used in an educational role to illustrate conceptual approaches to modelling of a particular science. Communication of models at this level is done through journal and conference paper reporting of refinements and case study applications, as well as being introduced in the education domain through lecture notes and text books.
- The next level (Level III) of development and application occurs when sufficient model case studies exist for flexible application to a range of situations, and where the model usefully describes some natural phenomenon at a level of detail, and with manageable data requirements, that are operationally useful. At this stage, managers dealing with operational planning or management analysis, such as forestry or river operations, access the model, often in conjunction with models of other aspects of the management system. In past times, the model has often had to be repackaged at this stage to make it more easy to use, and to improve linking with other models. Such repackaging should, and occasionally does, come with a re-examination of the concepts underlying the initial model development, and consideration of the range of situations for which it should and should not be used. The information on the model is supplied in user manuals or on-line help, and the limitations and assumptions of model use, made clear in previous publications, are generally given less importance in favour of more description of data requirements and usage.
- At the top level (Level IV), the model is most removed from the original development, and enters the realm of planning and policy analysis. At this level, packaging of the model can provide a complete separation between code and operation, and use of the model is often divorced from the underlying theory and concepts. At times, the users are not even familiar with the model workings, and the model operates largely as a black box. Communication of model issues largely focus on the differences between sets of results produced by a range of models runs, with the differences thought to be due to differing inputs rather than, say, artefacts of the model theory or construction.

At each of the levels described, the need for a model to be able to interact with other models increases, and the associated issues related to model integration expand. At Level I, it is sufficient and scientifically acceptable for the model to just represent well the natural phenomena that it attempts to describe. At the other extreme, Level IV, the interactions between the modelled phenomenon and other phenomena are often of more interest than any individual component. The levels of model development and associated integration needs are shown figuratively in Fig. 1.

The importance of the multi-level process is that, in light of the imperatives of Mode 2 science, integrated environmental management and participatory development processes, models are being developed with the intention of operating at different levels, such as Level I and Level III, at one time. This raises interesting technical and user issues, relating particularly to the depth of detail required at each level, representation of the science appropriate to each level, and the conceptual commensurability between models with higher amounts of integration. As scientists, we would like to move from, say, Level I to Level IV, with a minimum of effort,

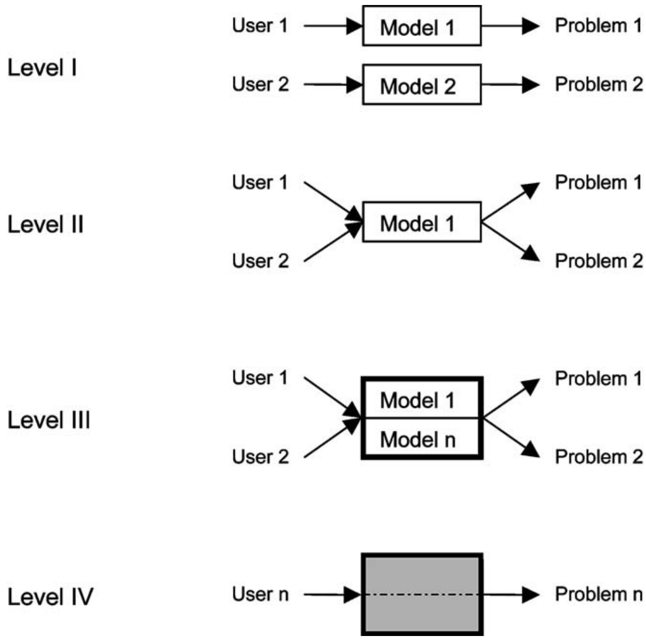

Fig. 1. Model integration at development and application Levels I–IV.

so that, if appropriate, the research-level model that we initially develop is not so different to the model sitting within an integrated systems application. At the same time, if such action is not appropriate, we would like to make as easy as possible, the transformations or simplifications required for use of the model at each level. Developers should be planning for integration right from the start, provided this does not bring with it heavy conceptual penalties imposed by the inflexibilities of modelling tools. New methods and techniques support this by providing approaches that allow single models to be developed individually and then to be slotted into integrated applications. Associated with such methods are the concepts of variable interfaces that provide users with only the amount of information and flexibility that is appropriate. The development of different user interfaces for a given model, such as the technical and public user interfaces of the Environmental Flows Decision Support System (Booty et al., 2000) and the interfaces for Regional Analysis by Intelligent Systems ON microcomputer (RAISON) (Lam et al., this issue) are examples.

This concept of multi-level application has some flaws, including data support across scales, willingness of individuals to operate this way, and modelling tools to support such approaches. To help in developing and solving environmental modelling problems, modellers access a wide range of data, with an associated wide range of data quality and relevance to the modelling task. For Level I modelling, where the model developer is the researcher, monitoring and data collection are often undertaken specifically to support scientific model development. At the other end of the scale, where, say, modelling is trying to deal with interactions between natural and non-natural systems, relevant data are often either entirely absent, or have been collected for purposes that provide little support for modelling. Thus the level of detail that can be confidently modelled with a given model varies with application and level of integration. For example, a traffic emissions model may be able to predict emissions from a given road section quite well, but when that model is applied to many roads, and linked to a forest air dispersion model and a human health model for different distances from the road, the limitations of data, and the requirements of the linked models, can affect the level of detail that can be represented well in the emission model, thereby requiring model simplifications or increased uncertainty on parameter values and results. For individuals, this kind of flexible and integrated approach to modelling is often challenging, as it involves change. It also involves openness, access and flexibility with concepts and code, which are not ubiquitous in the realms of scientific endeavour. Leaving aside these issues of support and individual preference, the question remains as to whether we have the tools and techniques available to support the modelling needs of the new millennium. The following sections argue that such tools and techniques have been under development for some time, and that emerging applications and modelling approaches not only support more flexible and adaptive modelling, but also make the job of modelling easier overall, providing scientists with the means and opportunity to focus more on science while meeting the needs of adoption.

3. Environmental modelling issues

When we consider the adoption of new tools and techniques, such as modelling frameworks and component-based modelling, for combining models from different disciplines into integrated management applications, we find that we are constrained both technically and conceptually.

Technically, our models are rarely designed to communicate with other models within our disciplines, let alone with models from other disciplines. This is very apparent in natural resource areas such as hydrology, ecology and forestry, where there is a considerable amount of legacy code in use, and we tend to view that code as our knowledge base, rather than the concepts and algorithms contained within. Textbooks (e.g. Singh, 1995) and libraries (e.g. Environmental Protection Agency, 1996) of models provide ample examples of legacy applications that often work well within narrowly defined limits, and which are difficult to integrate with other models and tools.

Conceptually, we are faced with problems at a range of levels. At the broadest level, difficulties arise from ontological differences between not only scientific disciplines, but also between science, management and broader social views of the natural environment. In these realms, our different views of the nature of the world require that we pay considerable attention to both our role as a scientific ‘expert’, the way that we represent our science to others, and to the context of application of our knowledge to an environmental management problem (Marsh, 2002). At the code level, where our concepts are expressed, we have a history of over 30 years of computer coding in some fields, and some traditions run very deep. How many readers have encountered recent code that contains numbered ‘continue’ statements, or uses #3 as the default number for input files? Hopefully these hangovers from early FORTRAN days are slowly being let go, and although they may not directly affect new code implementations, they are often indicative of particular methodological approaches to environmental modelling.

Irrespective of these practice hangovers, legacy models built using outdated practices are performing valuable functions and services across the spectrum of Levels I–IV development and application, long after the technology upon which they were based has been surpassed. Herein lies one of the key problems in integration—these models were generally designed to do a particular job, and are often not able to provide the features we now desire, such as flexible exchange of algorithms or connection with other models. Changing code is of particular interest to researchers operating at Level I, as we seek to update old code with new concepts, while Level IV usage of models demands the ability to consider flexibly different configurations of sub-models for different problems in a given location.

However, this problem of good knowledge bound in outdated code is reducing, as we create new models to tackle environmental problems that fit better with the changing nature of our data and knowledge, and the demands of environmental managers and Mode 2 science. When combined with a vanguard of recent graduates who have been schooled in modern software engineering techniques, there is an increased attraction in recognising that knowledge and code can be separated, and that it is knowledge that we are building upon, rather than code.

4. Development in environmental modelling with GIS

Current developments in environmental modelling and modelling tools owe much to a combination of factors arising from both computer science and software engineering theory, and changes in data access and use by environmental managers through tools such as geographic information systems (GIS). It is clear that over two decades the development of GIS has shown many environmental managers that not only are there more spatially explicit ways of looking at natural systems, but also that management decision making can benefit from the modelling available through manipulation of spatial data.

GIS were the first set of tools that provided a comprehensive measure of integration in the context of spatially focussed environmental management, in that they provided data management, analysis and visualisation tools in single packages. With the power available with GIS and the desires for integrated approaches to management through integrated modelling, there have arisen a host of example applications that address problems in atmosphere-surface systems, hydrology, forestry and biology (e.g. DeVantier and Feldman, 1993; Goodchild et al., 1993; Goodchild et al., 1996; Haan and Storm, 1996; Su and Mackey, 1997; Basnyat et al., 2000).

In hindsight, the success of GIS took us three steps forward and two steps back in the area of integrated environmental modelling. On the plus side, the use of GIS showed us that it was possible to bridge the gaps between scientific research modelling and management applications in a flexible and responsive way. GIS successes also resulted in conceptual developments about the ways that we collect and use spatial data in environmental modelling, and also highlighted the problems that needed to be overcome to get our modelling and data working together (Goodchild et al., 1993, 1996, 1997). Interoperability is one of the classic problems that has been raised, and partly solved, through the imperatives of GIS development and use. The interoperability debate largely surrounds the issues of getting data exchange between GIS working seamlessly, although it also covers broader semantic and communication issues of getting models to work together (Goodchild et al., 1997). This is a key issue, as data manipulation and exchange is fundamental to modelling, so for integrated modelling to work, data passing from model to model must work.

On the negative side, the tremendous success of GIS, and of modelling using GIS, has resulted in problems of framework inflexibility. In essence, GIS are often seen as the technical and conceptual frameworks into which environmental modelling must fit, rather than as being providers of services, primarily spatial data analysis and management, to environmental modelling. The difference between these approaches is illustrated in Fig. 2, where in one view of integration of GIS and modelling, the model services are either built into or accessed from within a GIS, while in the alternative view the GIS is seen as a collection of spatial data and other services, some of which are accessed from environmental models. In addition, there are metaphorical differences between GIS and environmental modelling that can affect the basic construction of models, and hence, the flexibility

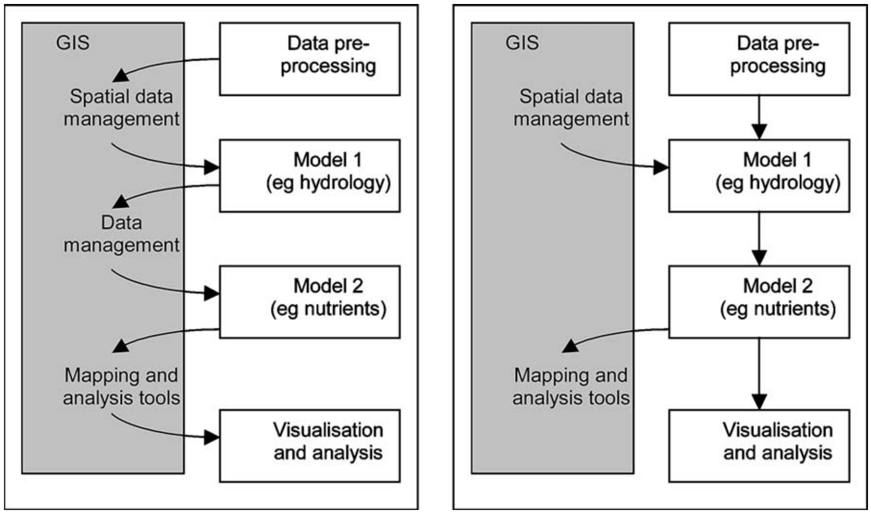

Fig. 2. Two views of GIS and environmental model integration.

and adaptability of a model in a given problem situation (Fedra, 1993; Raper and Livingstone, 1995).

The design and conceptual difficulties in integration of GIS and environmental modelling have been the topic of debate for some time now. A shift in focus from modelling using GIS to model-GIS integration can be identified by comparing the titles of the occasional series of international conferences on GIS and environmental modelling from 'Environmental Modelling with GIS' (Goodchild et al., 1993), to 'Integrating GIS and Environmental Modelling', in 2000. Despite this broadening of view, GIS still offer many modelling advantages, and application development within or based largely upon GIS continues (e.g. Aspinall and Pearson, 2000; Basnyat et al., 2000; McKinney and Cai, 2002).

Fedra (1993), Nyerges (1993) and Sui and Maggio (1999) present views of different levels of GIS and model integration (or coupling), with the 'lowest' level of linking being the use of GIS for preparation of data files for use in other models, while the 'highest' level of integration saw the GIS and the model being one unit, achieved by either building model functions into the GIS, or building GIS functions into environmental models. The availability of flexible scripting languages with GIS have seen many early examples of the former approach, (e.g. DeVantier and Feldman, 1993; Engel et al., 1993), while in recent times the development of spatial analysis and visualisation component-ware have produced examples of the latter (e.g. Argent and Mitchell, 1999; Rebolj and Sturm, 1999).

The integration of models with and within GIS have aroused a degree of research interest, aimed at exploring and solving some of the associated technical and conceptual limitations and issues. Abel et al. (1994) analysed the integration problem and presented a scheme that separated the working of models and GIS from the exchanges between them. They used an architecture-based approach that examined the types of linkages and services provided by each. Four basic services, or operations, were defined, namely transformation, construction, accession and filtering. Consideration of the provision and positioning of these services amongst model and GIS systems allows for construction and analysis of alternative integration schemes.

Livingstone and Raper (1994) and Raper and Livingstone (1995) moved away from a GIS-centric view of model integration by examining the structural context of the environmental modelling situation, selecting an appropriate higher level data model for framing the problem, and then selecting a modelling approach to suit. Object-oriented considerations, which were entering the environmental modelling domain at that time, were considered to offer advantages (Crosbie, 1996). This approach, and that alluded to by Fedra (1993) has similarities with that proposed by Denzer (2002), for the generic integration of environmental information and decision support systems. Similarly, and often in conjunction with, these developments in the application of GIS to environmental problems, there have been parallel developments in the area of integrated environmental modelling.

5. Developments in integrated environmental modelling

Environmental modelling developments have often arisen from consideration of the conceptual and operational limitations of dynamic simulation packages, such as STELLA™ or EXTEND™, rather than GIS. In a manner similar to the general incapacity of GIS to manage and model well using a temporally dynamic approach, dynamic simulation packages rarely lend themselves to good spatially explicit modelling. Developments in environmental modelling over the last decade have included both tools and modelling concepts, arising from:

- the needs for flexible model development, application and integration for users operating at development Levels I–IV, mentioned previously;
- technological innovation, and
- extension of ideas from areas such as commerce, computer science and software engineering.

Some of the early integrated environmental modelling developments were built around facilitation of exchanges between existing applications that involved both spatial and temporal data. The Gestion Intégrée de la ressource eau à l'échelle du Bassin versant, le Système Informatisè (GIBSI) is an example of such a system (Mailhot et al., 1997; Rousseau et al., 1997). GIBSI combines four legacy models (SWAT, RUSLE, HYDROTEL and QUAL2E) with a database management system and a GIS (GRASSLAND). Given this arrangement of specific legacy models, a fixed timestep of 1 day was used for temporal modelling, and the data passed between each model were of fixed format. The capacity of such a system to support flexible modelling needs, such as required by Level III or IV application, lay largely in the parameters used in the modelling rather than the modelling itself, and options such as different spatial systems and different time series data could be used to explore scenarios.

The RAISON system was originally developed on lines similar to those of GIBSI. RAISON, however was designed to offer a more generic approach to management of models, enhanced decision support, and expert system capabilities (Lam, 1997; Lam et al., 1997). Example applications using RAISON (Leon et al., 1997; Lam et al., this issue) illustrate the ability to encapsulate a legacy model, such as the AGNPS non-point source pollution model, within a broader framework. In these examples, AGNPS operates as a legacy system, while RAISON provides the support to collate, edit and analyse data, create files for AGNPS and run the model, receive AGNPS output and display them using alternative visualisations, and also undertake some sensitivity analysis by input manipulation. In this way, AGNPS is treated in a modular way, as a separate unit that performs a function, while RAISON acts in a limited capacity as a module management system, by managing the data handling, execution, visualisation and analysis functions. The level of tailoring needed to work legacy models into a system such as RAISON depends on the structure of the legacy model, the capacity of the management system, and the requirements for interactions between the master system and the legacy code component.

There have been a considerable number of developments for modular management of legacy models along the lines given above, as well as more generic modular environmental modelling, and they have resulted in various forms of environmental modelling approaches over time. One of the early developments in this area was the modular modelling system (MMS) (Leavesley et al., 1996), developed by the US Geological Survey with the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES). The system is quite robust and well supported, but has limitations is some application areas due to issues such as time stepping. MMS can be thought of as a semi-integrated system, with a database oriented approach to exchanging information between modules, and a shell or modelling framework for operation.

Development and use of modular and integrated modelling approaches raises technical, conceptual and operational issues. Model integration issues, in the context of linking and execution of models, were identified as being those largely associated with model representation, semantics, dimensionality, and component model management by the controlling system (Kottemann and Dolk, 1992; Dolk and Kottemann, 1993). The use of modelling languages, such as that supporting 'structured modelling' (Geoffrion, 1987) or the model description language of Muhanna (1994), along with appropriate process-oriented model interaction schemes, were suggested as approaches for supporting generic model integration.

One approach to the issue of integrating different modelling system components in a modular way arises from consideration of the parallels with federated database design. Abel et al. (1997) considered this approach and, using a water quality decision support system as a prototype, highlighted the importance of clear representation of the relationships between the modules used for numerical processing, and the data models used in the integrated application.

Appropriate system architecture is a key to ensuring that the data models and processing modules of our integrated modelling systems fit together. A limited open and extensible architecture for integrated GIS and environmental modelling applications was prototyped by Frysinger et al. (1996). In this system, which shared similarities to others being developed at the time (e.g. Lau et al., 1996), modular modelling services were provided by different applications, controlled by shell scripts, with geographical information tools, such as those provided by GRASS, being used as modules for handling spatial data requirements.

Extension of the integrated modelling concept to include model building and generic multiple model operations, such as those for optimisation, scenario exploration and decision support (e.g. Guariso et al., 1996; Rizzoli et al., 1998), resulted in development of framework-based approaches using object-oriented structures to support the system operation needs. These developments highlighted the architectural and object definition issues that arose in the modelling community as the object-based techniques, developed in computer science and software engineering, began to be applied in the areas of environmental modelling.

6. Objects and components applied to environmental modelling

Authors such as Livingstone and Raper (1994, 1995), Guariso et al. (1996), Abel et al. (1997), Bennett (1997) and Rizzoli et al. (1998) provided considerable insight into the technological and methodological changes associated with the adoption into environmental modelling of modern software engineering approaches.

Chief amongst these approaches is that of object-oriented (OO) modelling (Rumbaugh et al., 1991). There are a range of methodological approaches to OO modelling for environmental applications, but a common methodological starting point is OO analysis (OOA) of the problem situation, and identification of modelling system requirements, often through expression of usage scenarios, or use-cases. Basic system entities can be identified, and class hierarchies and classes, with associated attributes and operations, defined. To complete the OOA, object relationships, behaviour and communication are defined, and the results of the OOA carried forward to system design, construction and testing (Pressman, 2001).

In OO environmental modelling a key aspect is definition of the basic classes, ideally done so that the resulting model structure is flexible enough to support modelling of other, similar problems in the environmental ‘problem domain’. As a simple example, classes could be derived by function (e.g. rainfall-runoff class), by system part (e.g. soil layer class), by following a generic software design pattern (e.g. observer class), or by using some other basic conceptualisation. Each of these approaches has strengths and weaknesses, and no single preferred approach has emerged from within the environmental modelling community.

The aspects of OO approaches that differ from previously used environmental modelling methods, such as structured analysis or procedural methods, are communication, encapsulation, inheritance, and polymorphism (Pressman, 2001). Communication, inheritance and encapsulation have offered tremendous advantages to environmental modelling—communication methods have improved integrated modelling by relieving data and file exchange problems between modules, inheritance has allowed modelling systems to more readily handle multiple sets of similar objects, such a sub-catchments, and encapsulation has provided the means by which we can contain blocks of knowledge (be they called modules, components, models, routines or some other name) in discrete units.

This last point has provided not only technical, but also conceptual, support for the ‘module’ or ‘component’ modelling approaches that underlie recent environmental modelling investigations (e.g. Bian, 2000; He et al., 2002). Module based modelling concepts were developed in computer science and engineering fields during the 1970s and early 1980s (Zeigler, 1987; Clements, 1995) and have evolved through component-based software development (CBSD) into component-based software engineering (CBSE). CBSE has a design emphasis that focuses on building systems of software rather than on programming. The relevance and practical aspects of CBSE in environmental modelling have only fully become apparent in recent times. The use of components adopts an essentially unitary view, whereby a component is a single unit that does a defined job, and which can be joined with other components to form models. Object-oriented modelling supports this approach through both the theory of objects and the techniques developed for OO analysis, design and development.

For researchers working at any of the development Levels I–IV, the alluring prospects of integrated environmental modelling using components lies in an approach where modelling support services, such as data preparation, analysis and visualisation, are done by components made by someone else, leaving the researcher to concentrate on developing core model components containing the algorithms that represent their knowledge. In this way, new or different formulations of knowledge can be input into an existing model by transplanting one core component with another. Technical advantages arise from adoption of this paradigm when addressing the issue of re-development of legacy systems—by adopting component concepts we can identify where our knowledge truly lies, and separate it from mundane, but important, input/output activities. Adoption of this alluring prospect of integrated environmental modelling using components raises questions of construction, management and linking of components, and identifies the need for modelling frameworks, or environments, to provide these and other functions.

7. Environmental modelling frameworks

Modelling frameworks have been conceived of and developed for some time (e.g. Muhanna, 1994; Guariso et al., 1996; Bennett, 1997; Reed et al., 1999), with a varying range of features, determined largely by the requirements of the problem domain and the support needed by the underlying model conceptualisation. For component-based, integrated environmental modelling, desirable features include:

- A development environment, within which new

components can be built, possibly based upon existing components or component templates;
- A set or library of components that represent various pieces of knowledge—the so-called core components;
- A set of components that support common tasks, such as data collation and gap filling, basic analysis tasks, and output and visualisation options;
- An empty application interface (the framework) within which an environmental modeller would operate. In some instances this may contain a canvas upon which components are placed and manipulated in construction of a multi-component model;
- An integrated documentation system, that supports management for the components using a metadata based approach, possibly with the metadata being encapsulated with the component;
- A resource discovery system that allows users to identify and access components on a local machine or central servers, and
- A model execution system that supports multiple model runs, possibly through parallel processing, for optimisation, sensitivity analysis and scenario testing.

A number of frameworks have been developed along these lines in recent years. One example is the Interactive Component Modelling System (ICMS—formerly Integrated Catchment Modelling System). Development of the underlying structure of ICMS was initiated in the early 1990s in the form of the Open Modelling Engine (OME) (Rizzoli et al., 1998; Reed et al., 1999). The OME is an OO based approach with core elements consisting of:

- Class templates;
- Domain objects;
- Data templates;
- Data instances;
- Models;
- Model—domain object links;
- Inter domain object links, and
- A parser

The ICMS retains this underlying structure and makes it all available to the user, but has a user interface system that makes much of this complex structure apparent to the user only if needed. Once a model is constructed by joining components, the concept of alternative user interfaces for Levels III and IV application is supported through the use of an overlying graphical user interface (GUI), called an ICMS 'view'. A view is constructed, ideally through a stakeholder driven process, to provide a level of functionality that converts the 'manager speak', in terms of slider bars and other user-friendly features for manipulation of inputs, into control of the underlying components' variables.

One of the interesting aspects of component management in the OME is that of 'introspection'. Introspection is useful in that it allows a modelling framework to discover component properties by examination of the component at run-time, and to adjust its behaviour in response. A simple example of this approach is in the matching of component interfaces when linking components together in a framework. In broader application of introspection, such as under the Microsoft .NET™ environment, a framework can examine component properties, control component behaviour, make decisions about inputs and outputs, and automatically generate a GUI for operation of the component. This approach reduces workload on developers and also reduces the opportunities for mistakes made by misinterpretation of interface requirements or inappropriate linking between components (Meyer, 2001; Rahman et al., this issue).

The Dynamic Information Architecture System (DIAS) is another modelling framework, built by the Decision and Information Sciences Division of Argonne National Laboratory, USA, that has many of the features listed above (Sydelko et al., 1999). DIAS is based on OO principles, with considerable support for legacy code. Initial development, in the early 1990s, had its roots in the common model integration problems created by linking and compatibility problems between legacy models and new models. An OO based approach was selected for the system as it offered the best opportunities for surmounting the problems. As the name suggests, DIAS is built around architectural concepts, with the system providing the architecture or framework within which components can be constructed, modified and manipulated, and multi-component models created. In DIAS, all models and tools are treated as objects, including legacy models, which are registered and managed as individual classes. Other features from the above list, such as multi-scenario operation, model analysis, and local and distributed processing, are supported by the architecture.

Development of DIAS was influenced by defence, environmental and health applications, and example models include simulation of wind-generated wave transition processes in a marine environment, natural resources planning and ecosystem management, multi-aspect healthcare delivery management and the simulation of environmental effects on battlefield conditions (Sydelko et al., 1999).

Other object-oriented modelling frameworks that share similar concepts or features with ICMS and DIAS include the object user interface development of MMS, named MMS-OUI, the RAISON object system (ROS), the Tarsier modelling system (Watson et al., 1998), the Spatial Modelling Environment and the associated module specification formalism (Maxwell, 1999; Voinov et al., 1999a, b), and the Object Modelling System. The European Open Modelling Interface and Environment (OpenMI), being developed under the European 5th

Framework Programme project HarmonIT (Gijsbers et al., 2002), is one final example of a modelling framework that fits with the component-based approach presented here. This project is interesting as probably the most ambitious multi-national environmental modelling framework under development today. Communication standards for modelling, model linking processes, and representation of feedback loops and process interactions arising from this project will, hopefully, offer the integrated environmental modelling community a range of new and exciting modelling methods and tools.

8. Emerging technologies that support environmental modelling

Adopting a component-based approach to environmental modelling can bring with it a number of questions about relevant technologies and standards for developing and managing components. These apply both locally, in the context of a standalone component-based environmental modelling application, and more generally with the concept of distributed services, such as with Web Services used for internet-based data, component and application interaction (e.g. Rizzoli et al., 2001; Cameron et al., 2002).

The basic set of approaches are expanding, but a core set of component standards includes CORBA, COM and Javabeans/J2EE. These options have a range of technology and application dependent advantages and disadvantages, and selection of an appropriate standard should be based upon factors such as the standards already used in a problem domain, and the flexibility of the standard to provide the required functionality. The choice of a standard has varied considerably between developers of environmental modelling frameworks, and has normally been the result of a higher level decision about the technology used for actually building the modelling framework, such as with an integrated development environment (IDE).

The availability of general application IDEs has expanded considerably in recent years, largely due to demands for application development and web content creation tools for research, commercial and industrial uses. Although often built around commercial requirements, such as currency and transaction management, the features provided by such systems are also a boon to developers of environmental modelling applications.

Two recent developments have the potential to significantly influence the design and operation of environmental modelling frameworks over the coming years. The first of these is developer environments, such as Microsoft's .NET (Meyer, 2001) and Sun's Open Net Environment (ONE), and the second is the widespread adoption of the Extensible Markup Language (XML) for, amongst other things, data and component description.

Developer environments offer a range of features that include at least Web Services, an IDE, interchange standards, a component model and an object model, in what is essentially intended to be a complete toolkit for developers. In terms of usability, .NET and Sun ONE (using J2EE) vary in the classic trade-off between languages and platforms. .NET is currently built around operation on the Windows platform, but provides services that support model component development in languages that include C#, Visual Basic, C++, FORTRAN and Delphi. On the other hand, J2EE is single language, but operates on a range of platforms. From the point of view of integration of environmental modelling components, these approaches offer advantages in terms of developer support and usage. By enabling multiple language support, for example, it is possible for developers from a range of different backgrounds (with their traditional modelling languages) to develop components within a language with which they are familiar, whilst retaining a hope of integrating those components when complete. Thus one of the common issues in integration can be overcome. A system under development that utilises this, and other features of the .NET approach, is that of Rahman et al. (this issue). This work provides a lightweight modelling framework through a base-level kernel that provides only a parent class and optional metadata tags. With this as a starting point, and using fundamental .NET features, the newly developed framework uses a layered approach to support addition of features that include:

- Data type information and handling protocols, including checking of data bounds and type matching between data deliverers and data receivers. Built upon this can be automatic interface checking and matching between components during model construction, a key ingredient in improving integration tools and methods;
- The capacity to automatically generate user interfaces for components and for models made of numbers of components;
- Addition of analysis components and other data manipulation tools, and
- Addition of a range of visualisation tools, each one tailored to specific data types if required.

Thus, there is a tremendous opportunity for an approach such as this to provide a framework with the features mentioned previously.

One of the key technologies that supports .NET, and a range of emerging component and modelling endeavours is the Extensible Markup Language (XML). Unlike its language cousin HTML, XML does not use a fixed format but rather allows authors to define elements, identified by paired tags, for particular needs, in a manner that is extensible (W3C, 2000; Flynn, 2001). XML has a broad range of uses relevant to component-based environmental modelling, and has been used for both data exchange and display, and also for the specification of model component interfaces and data requirements.

In environmental modelling, XML can provide functions that range from simple metadata services to component interface definitions and model-to-data matching (Aloisio et al., 1999; Rana et al., 2000; Kokkonen et al., 2001; Rizzoli et al., 2001).

With the technological aspects of component-based modelling being largely solved through use of technology such as XML and developer environments, attention can turn to the more difficult issues of developing compatible modelling practice and description across and within disciplines.

9. Changing the practice of modelling using components

The previous sections have painted an optimistic view of the future of integrated environmental modelling, based of the technical feasibility of creating modelling frameworks to support component construction and linking, as well as model execution, data management, optimisation, output analysis and visualisation, sensitivity analysis and scenario exploration. The use of components allows component transplanting, or the so-called ‘plug and play’ approach. In this approach, a model ‘service’, such as a water balance algorithm encapsulated in a component, can be replaced by an alternative algorithm when appropriate, such as when looking at a different management problem on a previously modelled site, the same problem at a different time or space scale, or when new knowledge supports transplantation. This concept is elegant and attractive to many environmental science researchers as it offers the hope of a modelling paradigm where all the messy detail of data collation, manipulation, analysis and visualisation can be done using components that are designed by someone else to do this job, and the researcher can make new models by simply replacing one component with a candidate different or better component. The potential time and effort savings in adopting this approach are considerable, as are the reduction in technical challenges for the scientists who only have to build components in their area of expertise. The question remains as to whether, as researchers and modellers, we can effectively use this technology to cross disciplinary and conceptual boundaries, and build the integrated systems required to solve today’s environmental problems.

Application of the component concept to environmental modelling in an explicit way has been developing recently, and the advantages, disadvantages and challenges of this approach are now emerging. Bian (2000) highlighted the conceptual advantages of using components in modelling wildlife movement, including the ability to represent ecologically meaningful concepts, such as individual animals or animal groups, their behaviour, and their interaction with landscape. Lengthy discussion was also provided on the supposed differences, and advantages, of components over OO based modelling, such as component interfacing, level of abstraction, and scale of modelling. In developing and using modelling frameworks, such as those described previously, these differences are often irrelevant as the frameworks treat components, with their associated properties and operations, as objects with whatever level of abstraction and scale of representation that is appropriate.

Component interfacing was also highlighted as a key element for success in an OO based application of components to forest landscape modelling (He et al., 2002). In this work the development of standards for component representation and interfacing was emphasized as an important part of ensuring that the ideas of reusability and component transplanting are turned into practice.

The use of components and the development of frameworks for component construction, management and application in modelling raises considerations not only of interfacing, but also of data exchange and data models, common ontologies for modelling, semantics and the organisation of components and multi-component models (Bennett, 1997; Sui and Maggio, 1999; Duane et al., 2000). Technological approaches exist for solving data modelling and model and component management problems, but the sematic issues are those that present the next largest hurdle in integrated environmental modelling.

When using component-based modelling across disciplines, as is common in environmental management, we continually run into problems about the meaning of data, variable and parameter names that are loaded into, used by, or exchanged between, components. The difficulty lies with the detail, for when system components are built by different individuals, it is likely that misunderstandings will arise unless there is a clear and established meaning for various state variables, and concepts, and an agreed language for communicating these. Within disciplines this problem is recognised and particular semantic issues are acknowledged. Formal ontological methods, arising largely from Artificial Intelligence research, proposed for dealing explicitly with language problems in data and information management (e.g. Bordiga, 1995) may also be extended logically to component information and components.

Across disciplines, where we often have to alter our component models to exchange relevant information with other components, difficulties can arise with each new application. This issue has been recognised in many areas, and technical solutions, such as using XML to attach meaning to data and to components, are available. The work of Denzer (2002) is an example of the types of approaches that can be used. Additionally, the Sematic Web (W3C, 2001), which aims to improve the definition and communication of the 'meaning' of web information, offers methodologies that will assist data, component and model integration across distributed sources.

Outside of this technical realm, the solution to these semantic issues lies with the individuals involved and the process used for model development. By acknowledging at the outset that these difficulties exist, and will be expanded as we cajole our individual components into the larger integration picture, we can build processes of information exchange and explanation into the development. In time, as we gain experience in working with, and explaining our terminology to, members of other disciplines, we will develop a more semantically rich language of integrated environmental modelling.

10. Environmental modelling applications—issues for practitioners

The use of component-based approaches to environmental modelling thus offers an enticing future. Adopting this approach has, however, implications for both tactical and strategic approaches to our research.

Component model building, modelling frameworks, and the more general area of accessible software construction has been supported by the advent of visual modelling tools that allow for rapid application development and elegant user interface construction. These developments have narrowed the gap between the scientist/researcher developing a research tool, and the computer professional required to build an accessible user interface. The positive side to this is that it is easier for researchers to develop models that operate at more than one of the Levels I–IV of application, while the negative is the rash of poorly designed modelling tools that have been produced and very rarely used. Unfortunately, software failures are rarely reported in journals and other technical publications, so there is limited opportunity for us to learn from each others mistakes.

There are particular aspects of practice, however, that are supported by the new modelling tools and environments. For a considerable time, developers of environmental models have espoused the concept of user involvement in design (Loucks et al., 1985; Guariso and Werthner, 1989; Loucks and da Costa, 1991; Fedra, 1995; El-Swaify and Yakowitz, 1998), and recent shifts towards Mode 2 science and participatory environmental management also provide the impetus for such activities. In environmental modelling, where stakeholder participation at Levels II–IV requires both good science and good software, these concepts dovetail very well. With new software tools, modellers can rapidly construct alternative GUIs for component control in participatory workshop sessions, thereby providing instant support to stakeholders and the required good GUIs. At the same time, the use of component and object concepts supports good science by supporting clear representation of concepts in units that can be readily identified, described, changed and swapped, to suit the needs of researchers and managers.

Further consequences and opportunities of component-based approaches relate to the level (I–IV) at which development is taking place.

For researchers undertaking traditional Mode 1 science, working at development Level I, and not overly concerned about broad usage of developed models, the opportunity exists to access tools that allow model development time to be spent more flexibly and efficiently. Many researchers are forced to fit their representations of model conceptions into applications used for modelling. Examples such as Matlab™, Excel™ or ArcInfo™ bring with them the requirements for using a particular language and way of styling models. On top of this, there also sometimes exist additional requirements for manipulation of results of a model into a visualisation form separate from the application being used. The development of well serviced and flexibly designed modelling frameworks offers an opportunity to break away from this way of operating to provide a more flexible environment within which to model, ideally supported by suites of data management and visualisation tools. The negatives of this approach are that users have to learn how to use a new system, and particular analysis or visualisation tools may not be available. However, open standards of communication and connectivity within frameworks means that any particular visualisation or analysis tool can be built as desired. The scientist can then focus the larger portion of effort on scientific development rather than input and output design and development.

For researchers and educators operating at Level II, the benefits of this approach are greater than ease of model development. As an example, if all models taught in a particular course of study were developed and run in a single framework, with access to source code and data structures, students would gain the benefit of a common look and feel from their software, thereby emphasizing the differences in the underlying mathematical structure, rather than differences in user functionality. Any of these students who ventured into advanced study would then have the benefit of familiarity with a modelling approach that could be used as a starting point for their research, rather than having to learn a new or different approach for every new idea.

At Level III, the issues of integration really become apparent. At this level, individual components are brought together, and components are developed as part of describing a larger system view that is being researched or managed. The flexibility inherent in the system supports both flexible approaches to system representation and improved science.

At the next level of usage (Level IV), where the models enter the policy analysis and scenario exploration realm, the opportunities offered by flexible integration of alternative model components are considerable. During exploration of alternative environmental policies, the focus often crosses a range of physical and conceptual arenas, and such exploration may take a given component combination beyond the limits of reasonable use. In a non-component approach, the user has to live with the fact that the model has been moved beyond its intended limits and so must accept a higher associated degree of risk and uncertainty about the model results. With a flexible component system, supported by recommendations about appropriate usage of different components, the user is both encouraged and supported in changing model components as scales are changed. This has a number of benefits that include appropriate use of components, and, hence, better use of science, and clearer definition of knowledge gaps and uncertainties than is generally possible with traditional 'packaged' models.

Beyond these issues of application for individual developers, distribution, access to and control of components is a potential problem, although this can largely be solved through internet-based approaches such as those used in Web Services provision. Standard tools and protocols exist that could be used to develop component library services with degrees of functionality, accessibility and security. ECO-BAS (Hoch et al., 1998) is an example of a service that has shown the potential for managing and accessing models, and this can logically be extended to components. Similarly, public data services are also increasing for people in the environmental field, and, again, many of these could logically be extended to components.

Thus, for the practitioner there are already a range of tools and services that can be accessed to support practice at any of the four development and application levels.

11. Future directions and opportunities

This overview has shown that there are considerable opportunities for, and a number of barriers to, improving our modelling and management of environmental systems using components and frameworks. The progress being made in the technical development of components and frameworks, and the conceptual and semantic problems that are being overcome in integrated modelling applications, suggest a strong future for these approaches.

When these kinds of changes in practice and tool support start to become more commonplace, we can also step back further to our modelling fundamentals, and dare to think about approaching some of the 'givens' in different ways. One example of this may be in consideration of the representation of time in modelling. Traditionally, we have modelled temporally dynamic systems using either an event-based approach or regular time stepping. A new approach might encompass flexible time and space, whereby a model run can proceed using long time steps and large spatial units when little system activity is taking place, and shorter time steps and finer spatial units as activity increases. The JDEVS approach using atomic component concepts (Filippi et al., 2002) offers promise in this area.

From an integration standpoint, the frameworks developed to date, and those currently under construction, offer tremendous scope for the technical achievement of the modelling practice concepts espoused earlier. We still, however, have the problems within disciplines of developing agreed component structures as well as semantic issues across disciplines for us to overcome. These are not things that can be solved by individuals. By addressing these in a shared manner, possibly through shared cross-disciplinary development and communication, we can work towards are more successful application of knowledge in solving current and future environmental management problems.

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