A Literature Review concerning Integrated Natural Resource Management

Draft 1.0

Jeremy Cain
Institute of Hydrology

1. An Introduction to Integrated Natural Resource Management

1.1 What is INRM ?

For the purposes of this review, INRM will be defined as the coordinated management of all natural resources so as to ensure their equitable, sustainable and efficient use (Batchelor, 1995). These three principles of use require further elaboration.

The word equitable implies that all people who use the natural resources within the managed area have fair and equal access to resources in accordance with their needs. It is also recognised that resource use by one group of people may effect others. INRM will seek to solve any conflicts arising in this way by seeking a solution based on optimum benefits for all concerned.

Sustainable development is defined by the FAO (1990) as "the management and conservation of the natural resource base and orientation of technology and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development conserves land, water, plant and animal genetic resources, is environmentally sound, technically appropriate, economically viable and socially acceptable."

Resource use may be both equitable and sustainable but it can only be optimal if it is also efficient. In some senses efficient resource use is implied by the definition above. For example, efficient irrigation practices conserve water supplies. However there is also an economic dimension to the term. A particular resource use may be "economically viable" but increased efficiency of use, within the restrictions of equitability and sustainability, may bring increased economic returns. If the first two principles are adhered to then this can only benefit all resource users and is a desirable management objective.

To appreciate the full meaning of such definitions it is necessary to understand the generality of the phrase "resource use". Most obviously it implies the employment of natural resources in industrial and agricultural production processes and in human domestic consumption. Less obvious uses, perhaps, include the environment as a leisure resource and, although a non-consumptive use, the aesthetic contribution our surroundings make to our basic quality of life.

1.2 The necessity for INRM

In order to achieve the three principles of use defined above it is necessary to understand a highly complex system consisting, in its natural state, of inter-linked zoological, botanical and physical processes. Overlaid onto this and capable of effecting every aspect of it is human society, itself a mesh of economic, social and cultural interactions.

In human terms nature can be seen as a resource base, providing agriculture with fertile soils and industry with raw materials. While society as a whole values the outputs from each of these sectors it also values less tangible things such as "unspoiled" landscapes and wildlife conservation. More easily quantifiable, although perhaps less obvious, are the effects that agriculture and industry have on taxation through the environmental consequences of their practices. It is therefore must be concluded that "resource use occurs in a socio-economic context" (Breen et al., 1995).

The relative values placed on each resource use vary among and within different socio-economic groups. To achieve the best solution, management of these resources should seek to balance any competing interests while ensuring resource use is sustainable. To be a position to do this managers *must* be able to see the whole picture (van Zyl, 1995). This can therefore be seen to be a prime requisite of INRM.

It must be stressed that this cannot simply be a political process of consultation and compromise among different groups of resource users (although this is essential) as strategies designed to effect one resource may effect another in an unforeseen manner. It is essential for the manager to understand such links so as to appreciate the wider impact any action may have on the environment. This can only be achieved through a knowledge of what natural processes are present and how they operate together. In a hydrological context van Zyl (1995) pointed out that a certain land use determines not only the water volume required to support that use but also has an impact on water quality and groundwater availability. This, in turn, may effect human health. Science can help identify such linkages. Possible approaches to this will be discussed further in section 2.

1.3 Basic approaches

Numerous approaches to ICM are proposed in the literature, however, as pointed out by Maaren and Dent (1995), there is a widespread agreement that successful catchment management requires broad participation by all "stakeholders". Lindskog and Tengberg (1994) argued that "to design sustainable strategies of land management, it is essential to determine the symptoms and the causes of land degradation, both through scientific methods and from the perspective of the inhabitants of the area". The utility of this approach was recognised and adopted by the NRA which insisted on developing a planning process that provided an opportunity for wide consultation with all who those with an interest in the aquatic environment (Chandler, 1994). Blackmore (1995), describing the Murray-Darling Basin Commission's Natural Resource Management Strategy, acknowledged that successful long term change requires significant community involvement and that this involvement is vital if sustainable resource management is to be achieved. Such community involvement is best obtained through liaison with local institutions and community leaders.

ICM can therefore begin to be seen as a holistic process rather than a set of isolated management decisions and it is clear that this process must be cyclic. Various authors have presented conceptual models of this process (van Zyl, 1995, Breen et al., 1995, Slinger and Breen, 1995) but all contained the same basic elements. The state of the system to be managed must first be understood as must the impacts upon it. Proposals can then be formulated for its management which are then assessed in socio-economic, ecological and hydrological terms. Consultation with the communities living in the catchment is essential for proper assessment. Once this has been done, accepted proposals can be implemented and the impacts of the proposal on state of the system assessed. At this point the cycle begins again.

Another fundamental requirement for successful ICM is the establishment of effective institutions to facilitate the whole ICM process. Blackmore (1995) argued that at a political and bureaucratic level a critical ingredient for success is the creation of a management structure enabling matters of common interest to be discussed, resolved and implemented and that this usually involves several existing organisations coming together. He pointed out that this does not necessarily happen easily but suggested that "there is no more powerful stimulus than the distribution of wealth to focus political, bureaucratic and community minds on issues". This highlights the necessity of identifying the links between economics and environmental processes. However, the institutions must not only be established, they must also be effective. Mitchell and Hollick (1993) described how attempts at integrated catchment management in Western Australia encountered difficulties due to the roles of the different institutions involved in the planning process not being clearly defined.

1.4 The Land-Use and Land-Cover Change (LUCC) approach

Established in 1993, LUCC is a core project of the International Geosphere-Biosphere Programme (IGBP) and the Human Dimensions of Global Environmental Change Programme (HDP). It seeks to be a truly inter-disciplinary research programme with the general goal of improving the basic understanding of the dynamics of land-use and land-cover change with a focus on improving the ability to model and predict such change (Turner et al., 1995). Figure 1.1 below, illustrates the dynamics as the project perceives them.

The project has developed a far-sighted research structure which seeks to encompass all the challenges that will need to be met if the goal is to be achieved. It recognizes that contributions from a large number of disciplines will be required across a large number of subject areas and that these contributions must be well integrated. In order to achieve this, three inter-linked research foci have been formulated in conjunction with two integrating activities.

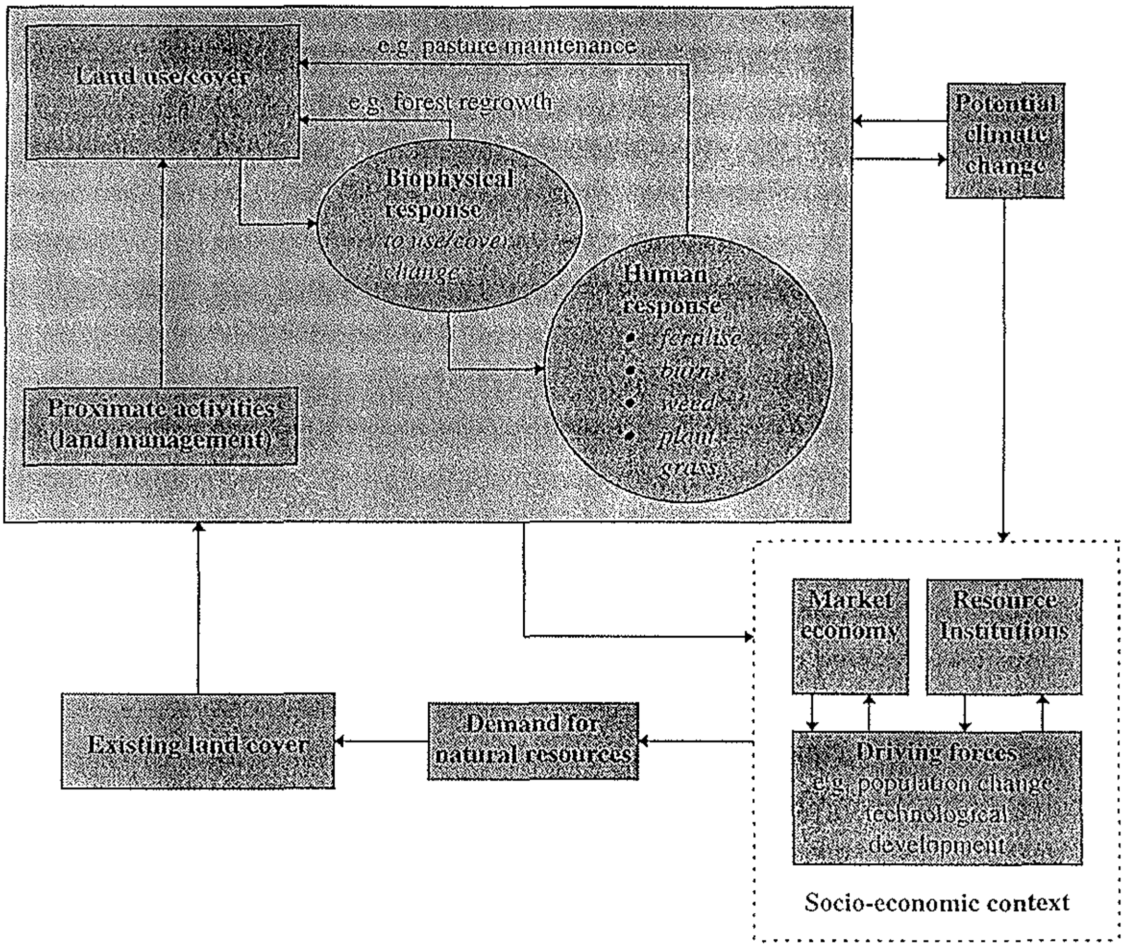

Figure 1.1 : LUCC Dynamics

Each research focus concentrates on a particular modelling approach. The authors recognize the deficiencies inherent in each of these approaches but assert that through integration each approach will complement the other.

Focus 1 uses a comparative case study approach to study the relationship between land cover and land use. It seeks to do this by developing a causal understanding of the dynamics active in the system under study through observation and measurement. Micro and meso-scale models can then be developed to represent the dynamics active at this scale. For these to be successful they must explicitly account for the local scale driving forces. These driving forces are divided into three dimensions as shown in figure 1.2 below.

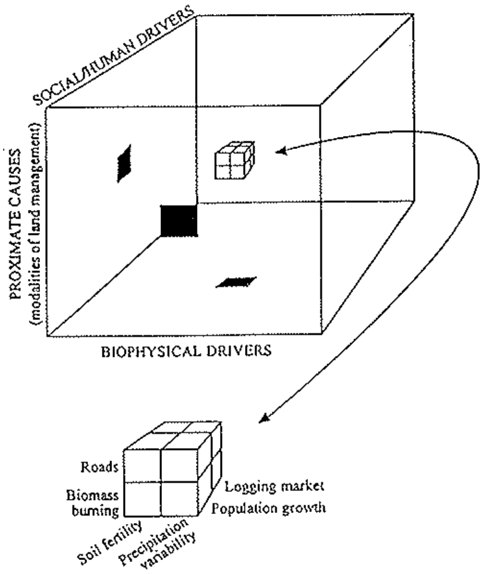

Figure 1.2 : Three dimensions of the driving forces of LUCC

Although there will be a multitude of driving forces operating at a range of scales it is argued that the behaviour of many natural systems can be explained by only a few of these operating at characteristic temporal and spatial scales. This is called the extended keystone hypothesis (Holling, 1992). These keystone processes can be identified through the models developed from the case studies. As these studies will have been carried out at a range of scales, the scale independence of the processes identified can be assessed.

Focus 2 uses direct empirical observations from remote sensing instruments, national censuses, land-cover inventories and field based measurements to calibrate empirical, spatially detailed models of land cover change. Such data, if available in sufficient temporal and spatial resolution, can be used to identify spatial patterns of land cover change. This data is seen to be primarily of use to physical scientists in estimating such things as the global carbon budget. In this case, up to date and spatially detailed information is considered to be essential. Using such detailed land-cover maps, point models (of the carbon cycle, for example) can be extrapolated using correlations identified between cover type and process function.

It can be seen that this modelling approach, although providing insights into which variables are important in certain processes (through correlation studies, as described above), gives no information about the underlying driving processes. It is essential, therefore, that such an approach is used in conjunction with the case study approach discussed above.

Focus 3 attempts to develop integrated regional and global models. The authors assert that model systems must be developed that are sufficiently disaggregated to describe economic systems which operate mainly at provincial or national scales yet can be aggregated to the global scale. They must be able to simulate the interrelated driving forces of land-use/cover change (see figure 1.2) and the biophysical feedbacks which are important at such scales. They must be designed to account for the major directions in land-use/cover change which appear likely over the next few decades and yet be flexible enough to account for the surprises that will surely occur.

Further issues concerning socio-economic driving forces must be considered when designing these models. Technological change has a large effect on land-use and therefore land cover. Studies have shown that such technological change is induced *within* the system and as such these dynamics can be incorporated into any model of that system. A model must also be able to account for the effects of policy strategies currently being pursued (purification technology, emission control, infrastructure investment and land reclamation, for example) and to be able to deal with the uncertainties inherent in the human reaction to these policies.

Integrating activity 1 concerns data and classification. The authors argue that to facilitate integrated research it is essential to define a standardised classification. In order to cover the varied needs of all the disciplines involved this classification would need to cover at least three descriptive dimensions. These dimensions are as follows :

- *descriptors concerning manipulation of land characteristics (based on geographical units)*
- *descriptors concerning the purposes of particular land use (based on socio-economic units)*
- *descriptors concerning the underlying biophysical and socio-economic conditions.*

Appropriate descriptors should be chosen so that the requirements of each of the research foci are met. Once such a classification has been defined, data collection can be geared towards placing each area of interest within the classification structure at a variety of scales. This will enforce a consideration of the overlaps between the different disciplines and so facilitate understanding of the linking processes.

Integrating activity 2 concentrates on the linkages between the temporal and spatial scales at which land use/cover change processes operate. This will be discussed further in section 2.3.1.

2. Modelling as a tool in INRM

2.1 *Why is there a need ?*

As discussed in section 1.2, for INRM to be successful it is essential that the links which exist between the socio-economic and environmental processes operating in a catchment are understood. At present, this understanding is incomplete. Slinger and Breen (1995) argued that one of the main inadequacies in existing environmental management procedures is the prediction of the environmental consequences arising from specific management actions. These actions have both bio-physical and socio-economic implications. Clearly the development and use of cross-disciplinary, inter-linked predictive models, with their potential to simulate these complex systems, can help overcome this inadequacy. This can be highlighted as a primary requirement in the full development of INRM as a practical methodology.

Recognising this, Plant (1993) stressed the utility of computer models in coming to grips with the unique complexity and uncertainty of environmental systems in particular. As a further function, he also proposed that such models, when part of an Expert or Decision Support System (see section 2.3.2 below) can aid in the transfer of knowledge about the management opportunities raised by rapidly advancing technology. He argued that the efficient transfer of this information is essential if worsening environmental problems are to be overcome.

The literature highlights, however, that this is only one example where a model can be used to provide more than just predictions of how a system behaves. If designed carefully it can also aid in :

- rationalising, directing and integrating data collection
- providing an understanding of how the separate components of a socio-economic, ecological and hydrological system interact
- communicating that understanding to a wide range of user
- monitoring the accuracy of its own predictions

Henderson-Sellers (1991a), in discussing environmental decision support, also supported this view of multi-purpose models. He stated that modelling studies should not only be used as a means of understanding the processes of the system but also as a planning and management tool. He argued that when applied in this way models might sacrifice scientific detail in the short term so as to gain the immediate advantages arising from their use as an engineering tool capable of solving real problems.

In agreement with the authors quoted above, Henderson-Sellers also recognised the unique potential of models to provide insights into the complexities of natural systems. He described situations in semi-arid countries where even small changes in urban drainage patterns, agricultural land use or meteorology can produce ecological changes in water which render it less potable or unsuitable for irrigation. He asserted that integrated modelling was the best way to understand and manage such complicated systems. In particular, he argued that the large database, which is a vital component of such a system (see section 2.3.3 below), provides the user with access to a larger range of case studies than those encountered within their own experience. This enables any decision to be based on a broader foundation.

It should be noted that numerous models already exist which are successful in describing the behaviour of a number of environmental systems from different disciplinary perspectives. In isolation, however, these models are not adequate to realise the full potential of INRM and methods of linking them within an integrated framework must be found. Only in this way will modelling be able to satisfy the needs identified above. This will be discussed further in the next section.

2.2 Model functions

2.2.1 Data collection

Burton (1995) recognised that model structure must be determined by the data available to that model. Due to the relative scarcity of detailed environmental data over a wide area, models must be able to cope with information collected at different times using a variety of methods, at different locations and at various scales (both temporal and spatial). Data may not always be quantitative and qualitative assessments by experienced experts may also be useful (and often may be the only thing available)- "common sense and expertise are more solid assets in an environment where information is very limited".

Montgomery *et al.* (1995) identified one of the reasons for unsuccessful land management systems in the past as haphazard collection of data without a clear set of questions or hypotheses. Collection, collation and integration of this data is therefore a challenge in itself, although preliminary modelling can help in identifying which data are most important and at what scales they are required. As part of this process different disciplines must come together to identify the type and scale of data which will satisfy the requirements of the whole project and true integration can be achieved to the benefit of all.

Data classification is a potentially useful way to guide and optimise the collection of data. This has already been discussed in the context of LUCC (see section 1.4 and Turner *et al.* 1995).

2.2.2 Understanding inter-disciplinary links

Burton (1995) indicated that a crucial factor in integrated modeling is the establishment of the links between the ecosystem components and how change effects these components as a whole rather than individually. Traditionally, modelling studies have concentrated on the interactions *within* these components. The major challenge now is to extend these models so as to incorporate the interactions *between* the components. However these components must be implemented in a flexible way so that they can be updated as understanding of the processes is improved (Montgomery *et al.*, 1995).

It is recognised that this understanding will be improved through the development and validation of integrated models themselves. Some model parameters will show greater sensitivity than others and may highlight the most important processes in reality. These processes can be studied further and consequently understanding will be improved. Alternatively prototype model validation may indicate that a vital cross-disciplinary process has been overlooked. Comparing model output to real data will reveal the nature of this process and allow it to be included in subsequent models.

2.2.3 Communicating understanding

It has already been argued that for ICM to be successful discussion amongst the stakeholders in the catchment is essential. Maaren and Dent (1995) asserted that the quality of such negotiations depends not only on the quality of the information available but on the understanding that all parties have concerning the implications of that information. A well designed model will aim to achieve this objective of understanding for users with a wide range of expertise. The transparency and utility of the software systems is essential to the credibility of any meaningful discussion process. The authors view an ICM model as a "living repository of knowledge" concerning the catchment which is readily accessible to everyone involved.

van Zyl (1995) supported this approach, maintaining that any data gathering exercise should seek to provide educational, training and communication material so as to enable effective participatory management. A well designed model using available catchment data will do this. As part of this, the model should be able to identify problems and needs as well as providing solutions and serve as a reference framework for all decision making.

In addition to the practical motivations presented above, Breen et al. (1995) pointed out that where public funds are used to support research programmes there is an implicit social contract for that research to inform public policy. Where it does not, it becomes discredited and loses public support.

It can be concluded that it is not sufficient for a model to act only as a highly specialised tool for use by experts but that it must also be able to communicate the understanding it can provide to a wide range of user. It can and should be the means by which an understanding of the processes active within a catchment can be reached from the data collected and it is essential that this understanding is achieved to an appropriate degree by all the stakeholders in the catchment.

2.2.4 Monitoring predictions

Breen *et al.* (1995) argued that it is not sufficient to simply employ predictive models due to their inherent inaccuracies and the potentially high consequences of inaccurate predictions. They proposed that it is necessary to continuously monitor indicators of the system response to management policies in order to provide a "safety net" for the predictive approach. Modelling could be used to identify which of the wide range of potential indicators could be best used to monitor system performance and thereby rationalise expensive data collection. Montgomery *et al.* (1995) reinforced this point. They contended that, as we cannot hope to understand the full detail of the system interactions, it is essential to supplement data collection for modelling with monitoring of the outputs derived from that data so as to check whether management objectives are being achieved.

2.3 Model design

2.3.1 Model scale

Montgomery *et al.* (1995) asserted that, as integrated modelling involves the consideration of multi-disciplinary processes, analysis should be organised around socially, economically, ecologically and hydrologically relevant units. The scale of these units will rarely coincide and therefore the model must be able to deal with data collected and processes operating at a wide range of scales. This is essential if the model is to encompass the full range of spatial and temporal variation inherent to human and environmental dynamics. The authors went on to argue that the catchment is the scale at which individual projects can be practically implemented and at which results can be easily aggregated to provide information over a larger area. Analysis at this scale can therefore provide the fundamental unit within a planning hierarchy which must be applicable at a wide range of scales.

The LUCC science plan (Turner *et al.*, 1995) indicated that while research shows that there are strong correlations between population, affluence and technology (the "PAT variables") and environmental change at continental scales at more local scales institutions, policy and other social variables are more important. It is necessary, therefore, that a cross-scalar model can deal appropriately with each type of data given the relevant scale. The authors recognised that, in general, individual models are only valid at the scale for which they were developed and that, as a consequence, careful attention must be given to consideration of such factors.

LUCC has defined the scaling problem be composed of two different effects. Firstly that each scale has its own specific units and variables and that, secondly, the relationships between these variables and units changes with scale. The challenge therefore becomes the identification of the units and variables at each scale and the relationships between them.

The solution they propose to these problems rests on the development of a hierarchical modelling and data collection approach. Different scales allow us to answer different questions and so models developed at all these scales should be used to gain a complete understanding of a system. This, in itself, will allow cross-scale dynamics to be identified. An preliminary conceptualisation of these dynamics is illustrated below in figure 2.1.

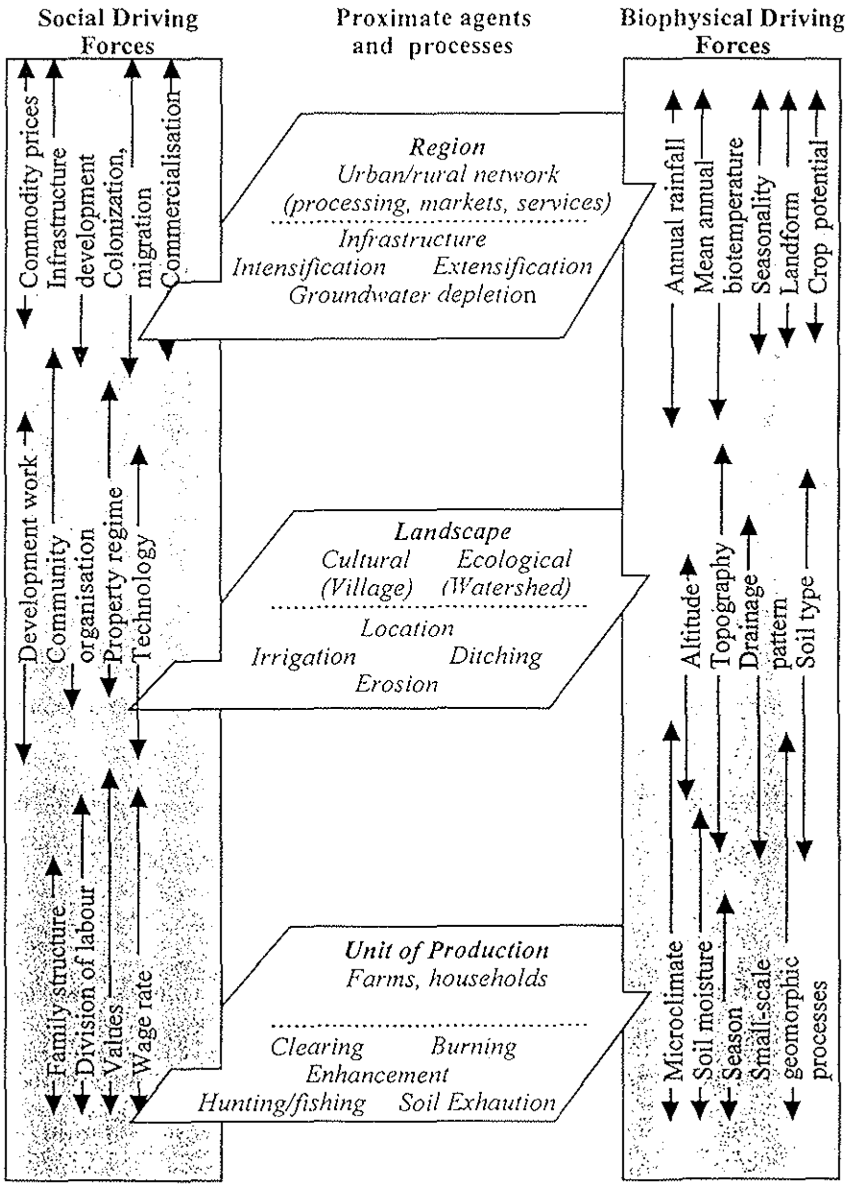

Figure 2.1 : Multi-scale driving forces in land use/cover change

2.3.2 Decision Support or Expert System ?

The above arguments strongly suggest that an integrated model which is to be used as a primary tool in an ICM process should be designed and implemented as either a decision support system (DSS) or as an expert system (ES). It is important to be aware of the difference between these two approaches. Stock et al. (1991) provide a useful definition. A DSS provides the user with information so that he or she is better able to make their own judgments. An ES, on the other hand, is designed to provide the user with advice as though from a human expert. When using an ES, the user is not expected to make judgments for themselves.

Having made this distinction, a choice regarding the approach followed must be based on both the application and the use. Breen et al. (1995) suggested that if research is to contribute usefully to sustainable catchment management the it should aim to promote the process by which decisions are made rather than promote a particular decision. This clearly indicates the use of a DSS as opposed to an ES, however the authors appeared to see their end user as a skilled professional. An ES may be more appropriate to the lay user, while a variety of users may warrant both approaches.

2.3.3 Modular frameworks

An approach to designing models to analyse this wide array of data is suggested by Slinger and Breen (1995). A range of simulation models may be linked together in a formalised framework and implemented according to the available data. Where detailed data sets are available, more complex models can be used while when data are scarce simpler models may suffice. This concept of a modular structure can be extended so that models are also implemented within the framework as appropriate to the output required by the user. As with the input data, when only simple outputs are required simple models may be used. A further benefit of this approach is the flexibility it provides to the more specialist user who may have a preference for one model over another. This flexibility will encourage the model to be more widely used- an important factor which will be discussed further in the next section. Practical methods of implementing such a framework are discussed in section in section 2.3.5.

2.3.4 Design for the user

Stock et al. (1991) asserted that for any computer system designed to support human performance the effectiveness of such a system can *only* be judged by considering both the computer and human components of that system. It is obvious that the easiest way to provide the user with what he or she requires, so ensuring system effectiveness, is to ask them. The approach adopted by Slinger and Breen (1995) to this involved extensive consultation with all those whom they hoped would use the system.

In agrrement with this, Masser (1994), researching the use of decision support systems within the Malaysian government, concluded that the effectiveness of such systems is typically measured by the extent to which they deliver the right information to the right people at the right time. A minimum condition to achieve this is that the overall information management strategy must be based on user needs.

Following this principle, Stock et al. (1991) designed a system to support management of forest ecosystems by first determining what the silviculturists (the user, in this case) wanted the system to do for them. They argued that it is essential to do this at the beginning so that the whole of the design process can subsequently be influenced by this. The system designer must consider the users' ability, understanding of the task, objectives, attitudes and emotions. Their research with the silviculturists raised a number of interesting points. A common complaint was that currently available systems were neither sufficiently user friendly nor adaptable to local conditions and user needs, and could not be used in an integrated manner. Stock et al. (1991) concluded that, for this class of user, the system should be fully transparent so that the user can see how the conclusions presented by the model have been reached.

Plant (1993) presented results of a similar survey carried out amongst users of a model based Expert System (see below). The most important features of the system identified by the users were user friendliness and ease of data entry

Henderson-Sellers (1991b) discussed the difficulties of validating environmental models. One of the main problems is that the modeller may have very different criteria for the success of the model than the user may have. This is explained to arise from different perceptions about the intended use of the model. All models perform less well in some areas than in others, however, if the model is optimised by the modeller to perform best in an area which is not of great importance to the user then the model will not be achieving its full potential. It seems, again, that discussion and development with users is the best way to avoid such problems.

A further point is raised by Chapman *et al.* (1995) whose experience of developing an integrated model highlights potential problems which can be avoided through user consultation. Considerable resources had been invested in producing a hydrological model component which subsequently had to be rejected by the funding agency because of doubts about the acceptability of a new model to the conservative minded water resource community. They concluded that specialists like to use the models they know and trust.

2.3.5 Model architecture

Henderson-Sellers (1991a) provided a good overview of the standard architecture of a Decision Support System. In general terms, DSSs "require the synergism of numerical models (usually simulation models) with large databases, front-ended by a man-machine dialogue component". They usually consist of three modules: a database management system (DBMS), a modelbase management system (MBMS) and a dialogue generation and management software module (DGMS).

The DBMS maintains the link between the user and the data stored within a database. It provides a transparent interface between the logical data structure required by the user and physical data structure maintained by the computer operating system. The MBMS plays a similar role as the DBMS and is able to cross-reference and link models within the modelbase. The modelbase contains a variety of numerical models each of which may be suitable to a particular study depending on the scale and quantity of data available within the database (a further deciding factor regarding model use may be user preference).

The DGMS can help select the most appropriate model by comparing the available data and the outputs required by the user with a set of stored model characteristics. These characteristics may include model name, purpose, limitations, data requirements, extent of validation and available documentation among others. The DGMS should also be able to provide an environment in which the user is comfortable working. Inputs should be requested and entered in a variety of ways (and should be error checked on entry) and results presented in a number of formats. These features should not be viewed as just "added extras". Without an appropriate and readily understandable interface, end users who may initially be unfamiliar with DSS methodologies will be unwilling to take up the new technology and no benefit will accrue from its development.

Jankowski (1992) focused on the use of the MBMS to store, invoke and link a range of numerical models in order to solve complex environmental problems. The concept of model integration and reusability can enable the most appropriate numerical algorithms and techniques to be applied to a particular problem helping the user to arrive at the optimum solution through new types of analysis. Such a system would consist of three architectural elements. The algorithms or model components ("atomic models") would be stored within a *modelbase* as building blocks. Integrated model derivation is then supported by a *knowledge base* which organises and classifies these components so that the most appropriate ones can be easily selected for combination into a larger derived model. This derived model can then be run via the third element- the *simulation engine*.

Plant (1993) described the standard architecture of Expert Systems as applied to agriculture and biological resource management. In many ways this is similar to that of a DSS, comprising a knowledge base and an inference engine supported by an appropriate user interface. The most important feature of this configuration is the separation of the inference mechanism from the domain-specific knowledge which is accepted as a defining characteristic of an Expert System.

Most commonly, the knowledge base consists of a series of production rules- if the antecedents A1 and A2 are present then the consequents C1 and C2 arise. The inference engine can then link these rules by developing chains of logical reasoning until the goal is arrived at, the consequents of the first rule become the antecedents of the second rule in the chain and so on. The descriptive nature of the rules enables intuitive information based on expert experience to be incorporated and can readily cope with the uncertainty inherent in the complex systems being dealt with. Not only can the user see the goal obtained by the system (the expert's judgment) but can follow the path of logical reasoning, enabling them to apply their own experience effectively.

Plant (1993) provided a number of examples of the practical use of Expert Systems in agriculture and, in particular, how these can be supported by the use of numerical models. Where the consequents do not automatically arise from the antecedents in a particular rule such models can provide this link. For example, an application deciding the most appropriate pesticide to use in particular situation might use a model to ascertain the consequences of using each of the treatments. An Expert System can then be used to determine the most suitable chemical to use based on the balance between the adverse environmental effects and the pesticide's ability to provide control as predicted by the model.

Maaren and Dent (1995) argued the need for architectural standards to be used in computer system development so as to avoid unnecessary dissipation of scientific energies. They reported that a number of major environmental bodies in USA are collaborating and have produced the Watershed Data Management System in an attempt to define some standards. These standards are now being adopted in South Africa.

3. A Review of Integrated Models

3.1 AQUA (Hoekstra, 1995)

3.1.1 General Overview

AQUA has been designed as a tool for integrated water policy analysis. It is composed of a simulation model linked to a framework of indices. The model consists of four structural units or submodels based around the water system as shown in figure 4.1 below.

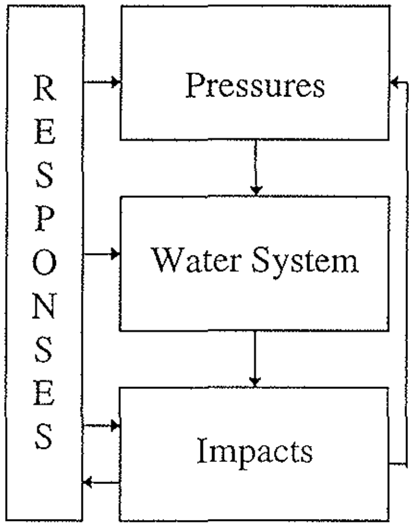

Figure 3.1 : Main structure of the simulation model of AQUA (from Hoekstra, 1995)

The pressures modelled are both socio-economic and environmental, these effect both the physical and chemical properties of the water system which in turn produce socio-economic and environmental impacts. These impacts may or may not produce responses which can effect all of the other four units directly. The physical, chemical and socio-economic processes are largely represented by calibrated empirical equations.

Although the representation of the processes is greatly simplified that model as a whole is extremely complex due to the large number of linkages between these processes. As a consequence, the model contains hundreds of state variables. These are rationalised by combining them mathematically in groups to form indices which represent system information in a more compact form. At the highest level the indices represent the pressure on the water system, the state of the water system and satisfaction with the functioning of the water system. This last includes such things as satisfaction with the levels of domestic and agricultural water supply.

3.1.2 The Simulation Model : The Pressure Submodel

The pressure submodel can be subdivided into environmental pressures and socio-economic pressures. The environmental pressures accounted for comprise land cover changes, soil degradation, temperature changes and changes in concentrations of certain substances in both surface and groundwater. They are not computed within the submodel but are fed into it either from other models external to the AQUA framework or from existing datasets.

The socio-economic factors are, however, computed within the submodel itself. Total water demand is calculated as the sum of domestic, irrigation, livestock and industrial demands. These components are effected by investment in education and technology, water price, gross national product and industrial output, among other things and are modelled by simple empirical equations. Elasticity in economic growth and prices are considered and through selection of different parameters varying technological development paths can be simulated. Actual supply may be lower than demand in some or all of these components due to water availability or allocation policy. Demand is therefore perceived as a potential demand which is not necessarily fulfilled. Actual water supplies are calculated in the impact submodel. Whether supply meets demand depends on the allocation mechanism simulated in the response submodel.

The actual pressure on the water system results from the actual supply. The pressure submodel differentiates between several different water sources which are used to meet that supply. These sources are fresh surface and groundwater, fossil groundwater, rainwater harvesting and saline water. The withdrawal of water stored in reservoirs is divided into that used for water supply and that used for hydroelectric power generation. Water taken from any of these sources may be returned to the same or another source through water recycling. This is simulated through the calculation of a water reuse potential parameter. Furthermore, return of domestic or industrial water to one of the sources may effect the water quality and this is quantified through another model parameter, itself a simple function of expenditure and treatment costs.

3.1.3 The Simulation Model : The Water System Submodel

At its largest scale of application, AQUA consists of four spatial compartments: the atmosphere, the land, the ice caps and the oceans. Within each of these compartments are one or more reservoirs. For example, within the land compartment lie reservoirs representing water in the following states : snow, soil moisture, contained in terrestrial biota, stored as surface water and stored as both fresh and fossil groundwater. When simulating land surface processes fourteen ecosystem types are accounted for comprising seven land cover types, each lying in two climate zones.

The volume of water within each reservoir is calculated through simple mass balance equations although it is assumed that the volume of water stored in the atmosphere is constant. In addition the storage in the snow and glaciers reservoir is modelled as a function of temperature. A variety of mechanisms are considered in the computation of the sea level including the global temperature (effecting any possible thermal expansion), land cover changes, reservoir construction and groundwater withdrawal.

The fluxes between the reservoirs (at least on land) are simulated on a monthly time step, considered essential in order to calculate the minimum freshwater supply throughout the year. The magnitude of the fluxes within a time step is calculated by simple empirical equations. For example, land evaporation is calculated using the Thornthwaite equations which are effectively a function of temperature only. Even simpler, the rate of evaporation from the ocean is computed as the product of a calibrated response parameter and a constant. The loss from the soil moisture store is a function of a soil water holding capacity parameter (given for each land cover type) and the potential loss, which is the difference between precipitation and potential evaporation above any soil moisture deficit. The actual evaporation is then the difference between the rainfall and the change in soil moisture storage. Runoff is empirically distributed between fractions which discharge to groundwater, run off the surface or occur as baseflow and the river discharge is calculated from a mass balance of all these quantities.

Four broad classes of water quality are distinguished by AQUA. Class A is suitable for all functions, B is suitable for humans but not for ecological development, C is unsuitable for both humans and aquatic life while D is also unsuitable for agriculture and industry. Depending on the scale at which the model is implemented, data on the average concentrations of relevant substances (such as nitrogen compounds) are either imported from an external model or calculated within AQUA by a simplified surface water quality model component. Groundwater quality is not considered. These average concentrations are statistically distributed and the fractions of the total water stock falling into each of the water quality classes is calculated. The thresholds between the classes are defined by maximum acceptable concentrations.

3.1.4 The Simulation Model : The Impact Submodel

The impact submodel simulates the performance of the following socio-economic and ecological "functions" of the water system :

1. Domestic water supply
2. Agricultural water supply
3. Industrial water supply
4. Hydroelectric generation
5. Flood protection
6. Natural water supply to terrestrial ecosystems
7. Protection of aquatic ecosystems

The first three functions are all calculated in a similar way. The supply is considered to be a function only of the balance between cost and expenditure. The expenditure is determined in the response submodel while the cost is calculated here as a function of the potential of the hydrological system to supply water, the quality of that water and the total water use. These parameters are modified by a calibrated constant dependent on the local costs in the are being modelled. The supply can then be compared to the demand (as calculated in the pressure submodel) to provide data on which to base policy decisions.

Hydroelectric generation is calculated as the potential for power generation modified by a factor quantifying the degree to which this potential is achieved. The potential is again a balance between costs and expenditure. The cost itself is computed as a function of the hydraulic characteristics of the reservoir supplying the power station.

Five hydraulic, three demographic and four economic classes are applied to the worlds coastline in order to characterise the impact of coastal flooding in terms of people and capital. A critical water level is defined as a function of expenditure on coastal defences and relevant natural factors. The probability that the sea level will exceed this is then calculated as a function of this and other natural factors modified by parameters specific to the hydraulic, demographic and economic classes. Based on this probability and the elevation of the coastline the number of people and value of capital at risk can be quantified.

The remaining two functions are computed directly from parameters such as evapotranspiration and water quality output from the water systems submodel.

3.1.5 The Simulation Model : The Response Submodel

The response submodel simulates the societal response arising from the performance of the water system. It distinguishes between an autonomous response and a policy response. The policy response is modelled simply by setting the value of a number of variables within the submodel. If these are not set then the default values are taken which model a purely autonomous response.

The policy variables have been selected following two criteria. Firstly they are taken from the variables used in water policy analysis by the Unite Nations and then, secondly, only the variables which can be directly related to the dynamics active in the other three submodels are selected.

The policy options fall into categories which can be defined as infrastructural, educational, technological, financial, legislative and institutional. When the variables representing the options in each of these categories are not set by the user the model performs simple empirical calculations to estimate the autonomous response. For example, if the no specific policy concerning waste water treatment is input then the model assumes that the autonomous response will be to maintain the existing level of treatment and extend it in proportion to any rise in waste water discharge.

3.1.6 The Framework of Indices

Unsurprisingly, given the variety of processes which it seeks to simulate, the outputs from AQUA are numerous. Certain quantities, termed indicators by Hoekstra, can be identified with these processes which can quantify their performance and so provide the user with the information required. In order to simplify analysis, indices are derived by simple mathematical combinations of indicators relating to particular areas of the system. These are then aggregated themselves to create a three tier hierarchical structure. At the highest level there exists only three indices : the Water System Pressure Index, the Water System State Index and the Water System Functions Satisfaction Index.

The Water Systems Pressure Index incorporates information concerning the water demand as compared to that available from the natural hydrological system, water supply and reuse efficiencies and on the level of pollutant emission. The Water System State Index includes information on freshwater quantity and quality as well as sea level rise. Water System Functions Satisfaction Index quantifies the performance of all the water system functions listed in section 4.1.3. For example the domestic water supply index is defined as the fraction of the population with adequate water supply and sanitation.

3.2 The NERC/ ESRC Land Use Modelling Programme (NELUP)

3.2.1 General Overview

O'Callaghan (1995) describes NELUP as a Decision Support System to aid in integrated land use planning through the modelling of socio-economic mechanisms of land allocation which both constrain and are constrained by the physical and ecological processes impinging upon them. A hierarchical system framework is used to conceptualise the relationships between the entities and processes recognised to be present in the system.

At the lowest level are the data describing the state of the system. The level above this comprises *physical* models which link the physical entities described by the data in the level beneath. Level three contains information concerning feedback control systems and their effects on the processes described by the models beneath. The fourth level focuses on the behaviour of living organisms in response to the environment (again as described by the levels beneath). The fifth level places individual humans within the system while the sixth is that of social organisations- the level at which humans interact.

Land cover is recognised as the pervasive link between market and policy forces (operating at levels 5 and 6), the ecology (operating at level 4) and the hydrology (operating at levels 2 and 3) as summarised by the land cover triangle (figure 3.1). These disciplines together embody the key dynamics in the system which are relevant to environmental decision makers. NELUP therefore focuses on providing algorithms which describe the dynamics active in the three disciplines and the interactions between them. In this way all the information necessary for a decision based on the consideration of all disciplines in appropriate measure can be derived.

The model is primarily designed to run at the scale of a large catchment although the hydrological model can provide information on a scale much smaller than this. However, so as to represent the processes active at level 5, representative farm models can be nested within the regional economic simulation (Oglethorpe and O'Callaghan ,1995).

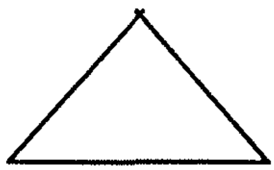

Figure 3.1 : Land cover triangle

3.2.2 Economic Modelling

As Moxey *et al.* (1995) explain, the economic component of NELUP seeks to model how land use changes as a response to the influence of changing market and policy conditions mediated through individual land users. This is considered to be the first step in simulating the system, after this the effects of the predicted land use change on the ecology and hydrology can be quantified.

It is assumed that the land users will make decisions based on maximising profit within technological constraints, however this decision can be influenced by a range of policy measures. To simulate these measures within NELUP, prices, quotas and subsidies can be fixed on range of inputs and outputs associated with the system.

A linear programming approach is used to model the socio-economic dynamics due to its flexibility and ability to cope with minimum data from a variety of sources. The approach involves defining a set of production activities in terms of input-output relationships. For example, in very simple terms a certain yield of wheat can be related to a certain quantity of fertiliser. The set can then be searched to find a combination of production activities which optimise an objective function (quantifying profit, for example) within the identified constraints (imposed by, for example, government policy).

All farms are considered to act as a single "macro-farm". Although it is recognised that this may overstate the flexibility and co-ordination of agricultural practice (in practice, most farmers will not work for the common good but will act in their own interests) it is an accepted technique. Spatial disaggregation is enabled by dividing the land within the macro-farm into categories distinguished by different potential production activities.

A number of other assumptions are made. Prices are assumed to be fixed outside of the system, livestock and feed purchases can be made outside of the catchment and forage transferred between land categories. In addition, agricultural technology is assumed to remain at a constant level and the benefits gained from it are independent of the scale on which it is used. Importantly, the objective function is chosen to be that as much land in the catchment as possible is returned to agricultural production and forestry. This implies that each producer will aim to maximise their profits.

3.2.3 Ecological Modelling

Rushton *et al.* (1995) state that the aim of the ecological component of NELUP is to predict the consequences of land use change on the distribution of the flora and fauna present in the river catchment. It is assumed that ecological change results from agronomic land use change.

In order to overcome the problems presented by an enormous species range and differences in behavioural response a non-process based modelling approach is applied to only a limited number of species. For further simplification two scales are selected for examination. The larger scale simulates change between species types while the smaller one looks at changes within species types. The species considered are also split into two groups : species assumed to occur in only one habitat (plants and insects, for example) and more mobile species with more complex habitat requirements, such as birds.

Three model types are applied depending on which scale and species group is being considered. The first, a simple associative model, is applicable to less mobile species at the larger scale. The second, the vegetation management model, deals specifically with plants at the smaller scale, while the third model type is applied to the mobile species group.

The associative model predicts species distribution according to their known occurrence in certain habitat types. A given land cover has a defined set of species communities present within it. Within these communities are defined a distribution of species. These definitions are base, as much as possible on published data.

The vegetation management model simulates the effects of grazing and fertiliser application on plant composition. Permutations of environment and management conditions (particularly with reference to the above) are known to produce certain plant compositions. Where these conditions are found within the catchment it is assumed that that plant composition is present. Any changes in, for example, the land management will result in a consequent species composition change.

The models applied to the higher species follow similar methodologies but due to the more complex behavioural patterns exhibited by such species they require more complex analysis. Habitat variables associated with certain species are identified using a GIS and the probability of a species occurring within a particular habitat is computed as a function of the degree to which the associated habitat variables are present.

3.2.4 Hydrological Modelling

Adams et al. (1995) outline the aims of the hydrological modelling component as being to predict the hydrological response of a river basin to proposed changes in land management. It can be seen once again, therefore, that land use provides the link between the separate system components. A two track approach is taken in doing this. A complex, physically based and distributed model, SHETRAN, is able to simulate the changes in water yield, sediment load and contamination to a high spatial and temporal resolution. However this approach requires a significant quantity of data and computational resources. Moreover, simulations at this level of complexity may not always be required or appropriate. In such circumstances a simpler model, ARNO, can be implemented. If this indicates effects which require further investigation then SHETRAN can be run off line to provide more detail. Both models will be described below.

SHETRAN models the catchment across a 1km resolution grid each cell of which is linked by a stream network to its neighbours. Lateral flow is modelled for both a surface and sub-surface processes, in both the saturated and unsaturated zones. Physically based equations are used to model the balances of water, sediment and contaminant at each point in the catchment and, when these equations are combined and solved, the spatial and temporal variation of the balances can be resolved. Effective parameters are used to represent the sub-grid variation in the physical and chemical variables which effect the processes being modelled.

ARNO, on the other hand, uses a lumped modelling approach. The model is applied to sub-basins within the catchment at a much larger scale than the 1km grid used by SHETRAN. The sub-basins are connected by a channel network which describes the primary river system and by explicitly defined surface water, unsaturated and saturated zone flow paths. Within each sub-basin the water balance is solved analytically and accounts for interception loss, plant and soil evaporation, storage, drainage and runoff.

3.3 Catchment Resource Assessment Model (CRAM)

Chapman et al. (1995) designed CRAM around three groups of components- a user interface group, a model group and a database group. The model group comprises five models- a runoff model, a reservoir model, an economic model, an environmental impact model and a social impact model.

Generally, the models are fairly simple and highly parameterised. For example, the economic model calculates a profit or loss by comparing the value of the land product to the costs. Production per unit land area is fixed for each land use and varies linearly with water availability. The total of the land use is then calculated by multiplying by a fixed price. There are fixed costs and variable costs proportional to the amount of product generated - pumping incurs a variable cost, for example, dependent not only on the volume pumped but on the distance and head it is pumped over. All these costs are set as constants within the model.

The environmental and social impact models derive an impact index from a weighted sum of values representing the state of ecosystem and society components under particular land uses. Among other things, these are weighted by the sensitivity of each component to different land uses.

3.4 A Multisector Model for Land Conversion

Yin et al. (1995) present a goal programming model designed to study the interrelations between biophysical, social and economic factors. It does not, however, attempt to model the interaction of the actual processes but uses constants derived from measured data to quantify the effects of land conversion from one use to another.

The mathematical approach used is similar to that employed by the economic component of NELUP. An objective function is defined to be the minimisation of the differences between target levels set by policy decisions and the actual levels predicted by the model. For example, if the target level is to produce 1000 tonnes of wheat, the model will attempt to allocate enough land so that the actual yield is as close to this as possible. This would be straightforward except that the land required may need to be allocated to another resource so as to achieve another target. For example, a high value may be placed on the preservation of habitats for water fowl. This can be quantified by associating a certain habitat value with a fixed land area. The total value desired then becomes a policy decision.

Such target levels form a set of constraints on the achievement of the objective function. The target levels are numerical goals representing the optimisation of resource production and economic return, minimisation of soil erosion and maintenance of forest cover and waterfowl habitat. As (in almost all cases) it will not be possible to achieve all the targets, the achievement of each goal must be ranked according to importance. The model will then seek to be as close as possible to the most important goal while not straying to far from the targets set for the others.

Values are calculated simply by multiplying the area of land under a particular use by a constant representing a value per unit land area. This value may represent soil loss or timber production, for example. The constants are derived from measured data.

3.5 Automated Land Evaluation System (ALES)

Rossiter (1990) describes ALES as "a microcomputer realisation of the FAO's framework for land evaluation (FAO,1976), suitably enhanced with a definite method of economic analysis". It provides a framework within which the expert knowledge of an individual user can be implemented in a structured way to produce land use classifications and linked economic returns. The end product is an expert system which can be used by non-expert land managers. However the construction is also an end in itself as it imposes a logic on the expert which aids in the understanding of the environmental system being modelled.

The system is composed of a knowledge base, a database, a processing module and a user interface. The knowledge base is central to the ability of the system to consider the interaction of biophysical processes with more abstract dynamics. It is a structured representation of all the facts and inferences that a real expert would consider when making a decision. For example, if it is desired to include the effect of land drainage on harvest date and consequent market price then this interaction must be represented in the knowledge base. The system would seek to model such an interaction by following a decision tree constructed *a priori* by the expert building the system. To continue the example, the actual effects on harvest date of installing land drainage must be identified by the expert from an *external data source* while building the system. To construct a decision tree this effect must be quantified for a range relevant parameters such as soil type, topography and climate.

This is the essential difference between this type of system and an approach based on process modelling. With the approach used by ALES, it is assumed that the expert knows what the effect of a particular management practice will be and can identify the interactions which produced that effect. The expert can then include these interactions in the knowledge base as a decision tree. The strength of ALES lies in the structure it imposes, forcing the expert to consider which processes and interactions need to be included.

The economic component seeks to calculate the gross margin resultant from the proposed use of a particular land type by comparing predicted costs with predicted returns. The predicted costs can be fixed or can vary and are dependent on land type and management practice. If more abstract costs, such as environmental degradation, can be quantified then they can be included here. The predicted returns are based on crop yield but may, again, include more abstract factors.

Once a model has been constructed and the necessary data collected then it can be run across homogeneous land mapping units to produce evaluation matrices. The physical suitability evaluation matrix allocates each land mapping unit a physical suitability class for each land use. A second matrix provides the gross margin calculated for each mapping unit under each land use and a third specifies the crop yield.

Johnson *et al.* (1994) integrate ALES within a methodology aimed at providing a complete system of resource management assessment. ALES is supplemented by simulation models which predict crop yields under given management regimes and whose output provides the basis for the decision trees built within ALES. In addition, a risk analysis of the economic returns generated by ALES is performed, dependent on biophysical and economic variables already calculated. The authors conclude that the ALES structure provides a useful way of integrating biophysical and economic data over a range of scales.

3.6 A Framework for Watershed Analysis

Montgomery *et al.* (1995) do not outline a working model but construct a framework for "ecosystem management" which raises a number of interesting points. Firstly their motivation for doing this provides a useful goal for any system development to aim at :

> *"Implementing ecosystem management requires a framework for gathering and interpreting environmental information at a resolution, scope and scale necessary for addressing the tradeoffs between economic and ecological considerations inherent to making land management decisions."*

Although this does not explicitly mention hydrology, it is recognised later in the paper that hydrological processes have an important effect on "ecological considerations".

The framework can be understood as a number of questions concerning the historical and current state of the catchment and its desirable future condition. Linked to each of these questions is an analysis component which comprises the actions required to answer that question. The framework includes such questions as "how does this landscape work ?" and "what has its history been ?" and seeks to integrate field analysis, historical analysis and numerical models describing the most important processes. Importance is placed on understanding what has happened in the past as a way of inferring the cause of current conditions. Such knowledge also provides a baseline from which to measure ecosystem stress which can be expected to increase as the environment is increasingly altered from the regime under which the ecosystem evolved.

The results from this analysis are then combined to classify the catchment into areas subject to similar ecological and economic interactions. Such a synthesis can be used to highlight the conflicts arising between the considerations pertaining to each of these disciplines and plans can then be formulated to resolve these conflicts.

3.7 Computer Models in Integrated Pest Management

Berry (1995) presents Hopper, a system designed to support real-time tactical decisions concerning grasshopper management at a local scale. Although not specifically aimed at natural resource management it provides a useful illustration of how a number of methodologies can be inter-linked to produce a system which truly responds to user requirements.

Hopper integrates and expert system with two simulation models and a linear programming model. The expert systems makes decisions regarding control measures depending on variables such as weather conditions and environmental concerns. The simulation models predict grasshopper populations and rangeland forage production. The recommendations of the expert system are then used, together with the output from the simulation models, as variables in a linear programming model which determines a cost-benefit ratio for the control measure proposed. The inputs and parameters used in the system can be easily changed to reflect any scenario the user may wish to investigate.

3.8 State-Wide Resource Information and Accounting System (SRIAS)

Mallawaarachchi *et al.* (1996) discuss the use of GIS capabilities in integrating data and mathematical programming model analyses. They have applied this methodology to produce the SRIAS system, designed to provide strategic answers to natural resource and economic policy questions.

"Best available" data sets, both physical and economic in nature, were collected and input to the GIS. These included data on land tenure, vegetation, geology, soils, topology, population and the current state of land degradation. The analysis then proceeds through a number of stages. In the first instance, agricultural production data is combined with soil and landscape data to produce a land-use map. This is done through the use of a linear programming (LP) technique which compensates for the limited data available at differing scales. The soil erosion hazard is then estimated using the Universal Soil Loss Equation and this data is then used in conjunction with another LP model to predict the net loss to the farmer of the estimated soil loss. The authors are currently working on using this economic value to estimate the wider implications of land degradation. For example, people external to the farm who normally add value to agricultural products will also experience a loss of income.

The capability of the GIS to analyse and aggregate spatial data makes it a useful tool in dealing with the problems arising from data which are only available at different scales as such data can be linked by common spatial attributes. The authors stress that this is only one application of the technique. They argue that the combination of GIS and modelling methodologies can enhance ecological and hydrogeological models to simulate the agro-ecological consequences of, for example, a change in irrigation policy on river salinity.

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