Models for Integrated Catchment Management

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Abstract
Models for Decision Support Systems (DSS) application have a fundamentally different function than those intended for research application. This difference in function naturally affects the form of the models which are most appropriate for DSSs. A critical evaluation of two models potentially available for catchment managers is carried out, using criteria developed from a consideration of the role and need for models in DSSs. Following perceived shortcomings in the utility of these models, the current development of an alternative approach for incorporating models in a DSS is outlined.

1.

1. INTRODUCTION

Research hydrologists are increasingly expected to produce outputs of direct applicability in catchment management. As a result, they are interested in integrating their research outputs into the decision-making process through incorporation into a Decision Support System (DSS). In principle, this meets the pressing needs faced by catchment managers. Indeed, there is a view that "*effective practice of ecosystem management is not possible without the aid of adequately powerful DSSs*" (Rauscher, 1995, page 1). However, experience demonstrates that although some effort has been put into developing "user-friendly" interfaces for research models[1], they have often proved not to be practical or relevant as **management** (as opposed to **research**) tools. Indeed, where research models that are of uncertain validity are made accessible through the addition of a user-friendly interface, this may seriously undermine the quality of decision-making by encouraging non-critical acceptance. Equally, hiding model assumptions and their implications behind such a user interface can encourage a natural inclination to select models on the basis of familiarity rather than relevance.

As a result of such experience, natural resource managers are increasingly sceptical about the role of "modelling" in management, in spite of their continued interest in integrating research outputs into planning. This disenchantment is reflected in the level of interest seen in knowledge-based and expert systems and other "simple" and "intuitive" (but often not very meaningful) approaches to integrating the current state of knowledge into the decision-making process.

In this paper we argue that modelling does have a practical role to play in management. The requirement for techniques for predicting the behaviour of land and water systems in terms of system properties and circumstances is only increasing and remains largely unfulfilled. However, we argue that where models are to be produced as management tools, this objective must dictate key attributes of model form and function. In this paper we present our views on the appropriate roles for models in decision support for catchment management and the consequent implications for modelling approaches. We then, undertake a critique of some current applications. Some general conclusions on opportunities and constraints for model integration into catchment management are also drawn.

2. ROLE AND FUNCTION OF MODELS IN DECISION SUPPORT

We begin with our central argument: that, **for complex systems, there is a fundamental difference between the requirements for models for hypothesis testing and those for decision support**. On the one hand, research may be viewed as an attempt to subvert or extend the existing paradigm (cf. Kuhn, 1963), by testing necessarily controversial (because they concern the limits of current knowledge) hypotheses. Such "research" models will reflect a somewhat idiosyncratic viewpoint about how the particular system under consideration behaves, and may be justifiably complex, difficult to implement, and data intensive. On the other hand, DSSs are properly concerned, not with controversy, but with the degree of certainty with which the behaviour of the system can be known under certain circumstances. Models for decision support must then facilitate canvassing the range of probable behaviours of the given system under a range of possible scenarios. Additionally, whereas research models may dictate what quantity and quality of data is necessary in order to choose between alternative hypotheses, DSS models must generally make do with data that is commonly and currently available.

An analysis of the needs of catchment managers for decision support indicates at least the following broad categories, which we suggest are roughly in priority order. Models for catchment support can provide:

- an educational tool, for learning about these inadequately understood biophysical systems. Through model structure, a model can encapsulate useful and valid (ie rigorous and self-consistent) ways of viewing the system, its processes and

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[1] By "research models" we mean those models which are primarily developed to facilitate an enhanced understanding of a particular system or class of systems. In its purest form, this involves some form of hypothesis testing. While this is often implicit rather than explicit, we highlight the hypothesis testing role of research models in this paper for clarity of contrast with models for management.

dependencies. This educational role in accessing state-of-the-art knowledge is, we suggest, the primary function of decision support models;

- an inferencing tool (as a special case of an educational tool), for understanding the consequences and sensitivities of model behaviour to varying assumptions, including parameter values. Note that the emphasis here is at least as much on the degree of confidence that can be assigned to estimates and predictions as on the estimates and predictions themselves;
- a communication tool for use between managers and stakeholders (particularly demonstrating due process in decision-making); and
- a framework for data collection.

This view differs from a more traditional approach to DSS in hydrological management which has tended to reflect an engineering perspective. Indeed, the development and use of DSSs more generally has evolved from a hard-systems, engineering, operations research background and has been most successfully applied in relatively well understood (particularly engineered) systems (Walker and Lowes, 1997). In these relatively simple contexts, it is possible to have models that can be argued to be 'correct' abstractions of the real world in the sense that prediction can be validated with a reasonably high degree of confidence. By contrast, models of complex and poorly understood biophysical systems (such as hydrological models of catchments) are more appropriately viewed as alternative arguments representing differing expert opinions about the way that the system in question might be seen to operate, and which are verifiable only up to a point. From this perspective the common view amongst DSS developers that "*... it seems likely that the importance of modelling techniques will be relegated to that of an analytical kernel buried in a DSS, with the emphasis placed on the quality of the decision rather than the elegance of the model.*" (Jamieson & Fedra, 1996) is unconvincing. Rather, we argue that elegant models (with well defined and testable structures and explicit statements of assumptions) are a necessary but not sufficient condition for quality decision support. So, while models may not be immediately visible this actually puts greater (rather than less) demands on their elegance. The emphasis on inferencing and exploration as a learning process, rather than directly generating a solution, also has important implications for model form and function (see section 3 below).

2.1 Models for learning

Decision support for catchment managers, based on the use of models, is more appropriately viewed as a learning process rather than as the application of an engineering tool. The alternative view is that managers are not interested in uncertainty, assumptions and hypotheses but are prepared to accept 'state-of-the-art' understanding about the system and the predictions that that understanding can provide as being 'correct' and use them in decision-making on this basis. The problem is that when this 'correctness' (in relation to the real world rather than assumptions) is open to challenge or, worse still, demonstrated to be significantly flawed, this seriously undermines the credibility of attempts to manage resources rationally on the basis of best available understanding. This in turn opens the door to a growing post-modern influence in resource management that challenges any role for science and resource management professionals (Gross and Levitt, 1994).

So, models do have an important role to play: but this role must be carefully considered and not overstated. We argue that it is more important that models help managers to generate insight than answers of uncertain validity, and that it is better for the decision maker to come to conclusions that are informed and vaguely right than to ones which they **believe** to be correct but are **actually** precisely wrong.

2.2 Models as inferencing procedures

The use of models as inferencing tools for prediction is perhaps their most common (but, we argue, not their primary) use in current DSSs. Of greater significance for management decision support is their ability to facilitate exploration of different scenarios, involving a range of different assumptions. As most models are more or less defined by their structure, which is itself determined by the particular choice of assumptions and simplifications which the modeller feels to be appropriate, scenario exploration with any one model is generally restricted to variation of model parameters within the given structure. In order to provide necessary flexibility and satisfy management needs for demonstrating robustness or otherwise of model predictions, some means of relating models associated with different sets of assumptions (or structures) is required; ie, a classification scheme or taxonomy of models is necessary. Such a classification scheme will have to take into account differences in input requirements (data) and outputs, as well as assumptions. The alternative of a "universal" model based on minimal assumptions for complex systems is simply not viable due to problems of complexity (of structure, parameter interactions, implementation etc.), and prohibitively expensive data requirements.

2.3 Demonstrating due process

Integrated resource management at a catchment scale is a complex process generally involving multiple stakeholders. As a result, explanation of opinions or decisions and defensible justification of the basis for them is critical. This is most clearly apparent in demonstrating 'due process'. All levels of government are being held increasingly accountable for their decisions such that managers are increasingly required to defend their recommendations or decisions and the process by which they were made. With the introduction of initiatives such as ISO 14000 (Tibor, 1996), this requirement to demonstrate 'due process' may be increasingly felt by industry as well as government.

Models for management may play a significant role in this process of communication on the basis that "*Openness about how decisions are reached is greatly facilitated through the use of a DSS in which the effects of alternative development policies can be explained and their impacts assessed in a form which can be* *comprehended by the non-expert*" (Jamieson & Fedra, 1996). However, this will only apply where the assumptions upon which a model is based can be varied, and the implications of those assumptions are available for inspection and criticism.

2.4 Models as data acquisition structures

Catchment-scale resource management will generally (but not inevitably) be constrained by data. Prioritising data collection poses serious challenges for the catchment manager. In the context of hydrological data, inappropriate spatial and temporal frequency in data collection can lead to data sets which contain limited information in total or, alternatively, significant expenditure on collecting data with rapidly diminishing information return. A well formulated model will provide a useful framework for decisions about data collection, and also provide a logical framework with which to demonstrate the relationships and dependencies of the various forms of data. Alternatively, under conditions when the availability of data is strictly limited, use of an appropriate model will maximise the amount of relevant information that can be extracted from the data (although, contrary to popular belief, it is not possible for a model to supply missing information)!

3. IMPLICATIONS FOR MODEL FORM

We have stated our belief that models designed for decision support will differ significantly from those intended or used primarily for research. Specifically, we may expect differences in the **form** of the models as a direct consequence of their difference in **function**. Differences in form may be discussed in terms of differences in requirements for input/output, flexibility and complexity. For the sake of clarity, we emphasise the distinction between research and decision support requirements, though in practice this is rather more a difference of emphasis or degree than the dichotomy we present here.

3.1 Input/output requirements

In models for research, data requirements are largely determined by the hypotheses which are to be entertained or tested. Generally speaking, at least some necessary data will be unavailable or of insufficient quality for the purpose, and an experimental program will be designed to acquire this data, often involving considerable effort and delay. Conversely, decision support models must generally make do with currently available data (in the interests of time/economics or capability), which is often sparse and of relatively poor quality; where information is unavailable it may have to be obtained from surrogate data through the invocation of additional assumptions. Increasingly, as the cost of remotely sensed data decreases and its availability increases, there is incentive to use this form of surrogate data as the input to models. Only if crucial information of direct relevance to the desired decision is unavailable will there be sufficient impetus to invest in further data acquisition, and this will be moderated by the anticipated time required to collect useful information. In decision support models, therefore, initial availability of data or information will have a much greater effect on model form than for research models.

3.2 Flexibility requirements

In contrast to the research arena where models are developed specifically to answer pre-posed questions or hypotheses, viable decision support systems for catchment management must take into account the constantly changing legislative, social, political and economic environment. They must therefore be designed to handle a range of decisions, the precise details of which are not *a priori* known, so that a large degree of flexibility is required. The type and detail of the information required (and hence the nature and quality of the requisite data) should be determined by the particular characteristics of the decision to be supported; and this in turn will largely determine the characteristics of the preferred model. Because of the inherent uncertainty in the nature and type of decisions to be supported, it will be necessary to deal with almost a continuum of variations in scale (both spatially and temporally).

Not only must the sensitivity of the model to variations in parameters be investigated, but the consequences of different model structures (arising from varying assumptions) may be of even greater importance. This is particularly true for environmental systems, where lack of consensus on system understanding means that state-of-the-art knowledge is really a collection of relatively disparate viewpoints on all but the most basic aspects, with this lowest common denominator of agreed knowledge of little real value. The implication is that for much DSS work, no single set of assumptions is likely to be adequate. This places increased emphasis on the need for DSS models to have well understood and explicitly stated assumptions, as well as compatible inputs and outputs.

3.3 Complexity

The traditional and very successful process-based approach to the scientific understanding of natural systems has been one of progressive disaggregation. System understanding was progressively refined by isolating a part of the system, and characterising its behaviour in terms of measured characteristics, in terms of "processes". Such processes inevitably tend to be relevant to smaller spatial scales than the original system.

There has been much less emphasis on the complementary methodology of aggregation – of precisely how these individual "processes" fit together to produce observed system behaviour, and the significance of individual contributions to the whole. It is often assumed naively that one can simply "sum up" small-scale behaviour to obtain that of the whole system. This methodology is flawed for several reasons.

Even when models of individual sub-systems are parametrically parsimonious, the combination of several sub-systems will lead to a composite model requiring the estimation of a relatively large number of parameters. Unless the available information has an effective number of degrees of freedom which exceeds the number of parameters to be determined, additional assumptions (not supported by data) will have to be made in order to obtain unique values for the parameters. For decision support, as noted above, information is usually at a premium, so that complex models cannot be recommended. In any case, searching a high-dimensional parameter space will generally result in parameter estimates which are highly correlated, and with large uncertainties.

Another serious flaw evident in aggregation models is the assumption of model structure. Whereas model structures for individual sub-systems may be more-or-less defensible, it does not follow that any arbitrary combination of such sub-systems is appropriate, without independent and rigorous testing of the structure using system-scale measurements. For low-complexity models suitable for decision support systems, it would appear to be preferable to analyse system-scale behaviour in terms of system-scale data, and only then to attempt to understand the resulting structure and parameter values in terms of smaller scale processes and parameters. This methodology then casts light on the relevance of individual small-scale "process" contributions to observed large scale regularities or processes. It is probably not reasonable to expect that the system scale parameter values can be calculated from those of the sub-system models, except in idealised cases.

4. CURRENT APPLICATIONS: A CRITIQUE.

In this section we carry out a brief critical analysis of two applications of models to management support, as an illustration of the above ideas. Although both these models have undergone significant development by both the original authors and others since their introduction, for the sake of simplicity and coherence we restrict our analysis to the basic or original form.

4.1 AGNPS: Application of "research" models to management

Young et al. (1989) describe the development and application of "a nonpoint-source pollution model for evaluating agricultural watersheds" (AGNPS). The model attempts to couple together sub-models (for hydrology, sediment generation and routing, and chemical transport) gathered from divers sources, including those intended originally for hypothesis testing. The hydrological sub-model is deliberately event-based. Sediment generation uses the universal soil loss equation (USLE) approach (entirely empirical); whereas routing is characterised by a fairly complex model involving concepts of stream power, and different transport rates for different particle sizes. Nutrient transport is modelled using the concept of "enrichment ratios" (particulate-borne) or "extraction coefficients" (soluble).

As with any model, there is a hierarchy of simplifying assumptions explicitly and implicitly invoked with the model. Perhaps the most significant of these in the classification of this model is that an event-based approach is necessary to adequately represent the transport of sediment, nutrients and other materials. This assumption dictates that sediment and nutrient generation and routing is driven by the hydrology, and hence the broad choice of sub-models and over-all model structure. Each sub-model then makes a number of more-or-less independent assumptions, whose compatibility is not always clear. For instance, the use of a time invariant "extraction coefficient" to characterise the yield of soluble materials implies the assumption of a time-averaged approach for nutrient concentrations which is at odds with the event-based hydrology and sediment routing sub-models.

The level of complexity of the various sub-models is also not balanced. It is assumed that the hydrology can be satisfactorily characterised in terms of total event discharge volume (a function of "curve number") and peak flow; but a non-linear sub-model for the latter alone involves the effective determination of six coefficients. The highly empirical sediment generation sub-model is contrasted with the more theoretically-based sediment routing sub-model (with numerous other parameter determinations), and the simplistic nutrient generation and transport sub-models. The overall effect inevitably is of a highly parameterised, but poorly balanced, model which gives a very idiosyncratic view of the possible behaviour of an agricultural catchment.

Implementation of this model, particularly in a setting other than that for which the empirical relationships were derived (ie USA agricultural areas), has relatively onerous input requirements; but data requirements for true validation are simply prohibitive. In common with authors of similar models, these authors have a highly optimistic view of the value of their model for prediction. It must be recognised that the choice of assumptions implicit in such a model involves interaction with the data to which it is to be applied, so that true "validation" is unlikely to be achieved by the creators. An indication of the possible deviations from real system behaviour is much more likely to come from semi-independent analysis, such as that of Panuska et al. (1991); but some bias towards the model from such sympathetic reviewers can still be expected. These authors found discrepancies of up to a factor of four in peak flow prediction, and more than an order of magnitude in sediment yield prediction; deficiencies in some model assumptions were associated with this lack of predictivity. A full classification in terms of assumptions, and analysis of the consequent inherent limitations of the model is clearly possible, but beyond the scope of this brief critique.

In summary, from the point of view of decision support, use of AGNPS is severely impeded by input requirements, and is too complex to allow reasonable validation, or for demonstrating due process with any degree of confidence in the predicted outcomes. It fulfils a useful function in suggesting the sort of data which might be required, and possible interactions between (say) the hydrology and sediment transport, but is limited by an inflexible and idiosyncratic structure, and unstated assumptions.

4.2 CMSS: A simplified approach to hydrological decision support

CMSS describes a model "*that analyses the likely effects of land use and management policies on the nutrient loads delivered to rivers*" (Davis and Farley, in press). Unlike the hybrid model discussed above, this model appears to have been designed for management use from the beginning: it facilitates the use of data of varying quality; it provides for some variation of assumptions; and it provides a mechanism for reviewing the context of predictions and an estimation of "uncertainty". Considerable effort is expended in providing a useable methodology for exploring the effects of varying land use and management policies on nutrient exports, quantifying necessarily qualitative and subjective input data.

At the heart of the model is the assumption that the contribution of a "spatial unit" to the nutrient load of the river is proportional to the product of the area (for diffuse sources) and a "generation rate". The generation rate is assumed to be a function only of land use, but this requirement in turn influences the number of distinct land use classes which are defined. For instance, land use can be regarded as a function of topography, soil type, climate and any other variable which is thought to influence nutrient generation rate significantly. Like AGNPS, the treatment of spatial organisation within the catchment is crude, though it is possible through the definition of land use classes: the generation rate for any nutrient is constant for a given land use class. Errors introduced through simplifying assumption are sensibly regarded as contributing to the uncertainty of the estimate, but the treatment of uncertainty is also very crude and unconvincing.

CMSS uses classified inputs, with continuous variables such as the mean annual rainfall distribution divided into a number of discrete classes. The number of effective "land uses" should then be the combined product of the number of classes for each significant factor; but in practice this is significantly reduced by combining classes with similar generation rates. Generation rates and uncertainties for each class are then determined by a combination of literature values and local (expert) opinion, with missing data obtained from "similar" land uses elsewhere. This data requirement is significant, and could be prohibitive without the *ad hoc* application of a great deal of pragmatism. The alternative procedure of using a parametric approach, such as the use of the USLE in AGNPS, would seem to be preferable, with no significant disadvantages, and without the "noise" introduced through the use of arbitrary classification boundaries. In fact, given the method of derivation of the USLE using long term average data, its use in CMSS (for application in the USA) seems rather easier to justify than its use in AGNPS for individual storms.

The most important difference between CMSS and AGNPS for the current purpose is the effective assumption of steady-state in CMSS, so that generation rates are constant in time (or, more realistically, that such fluctuations are averaged over a suitably long period), and not event-dependent. This ensures that the generation rate is the export rate, and implies that the characteristic residence time of nutrients in the catchment system is short compared to the averaging period. For catchments whose hydrology and material transport is dominated by infrequent major events, such assumptions will seldom be justified, and the analysis is limited to management practices which affect mean generation rates, and effectively ignores options which focus on particular parts of the hydrological cycle.

In summary, CMSS appears to be a useful model for decision support in the narrow area for which it was designed, but with fairly exacting input requirements. There is some flexibility in data requirements, and in the type of management options that can be considered, within a narrow range, but as a structure to guide data acquisition the model is probably too simplistic. Model assumptions are fairly rigid and restrictive. The simplicity of the model structure has allowed a genuine attempt to be made at providing explanation and uncertainty estimates for predictions, and consequently the model provides a reasonable educational tool if assumptions are properly recognised.

5. SYNTHESIS AND CONCLUSIONS :THE GENESIS OF AN ALTERNATIVE APPROACH

In this paper we have argued a fundamental difference in objective and, therefore, form and function, between models developed for research and for management. We have argued that this distinction has frequently been lost, to the detriment of researchers and those trying to use inappropriate tools for management. We have argued that hydrological models are useful predictive tools for use in management but that the 'state-of-the-art' inevitably limits the confidence that can be placed in output. As a result, models for management are more appropriately viewed as learning tools, particularly with regard to exploring the assumptions that underpin model structure and the implications of those assumptions. This ethos encourages decision making with due regard for the uncertainty associated with the understanding from which decisions are derived.

This explicit consideration of assumptions illustrates the need to seek means of generating locally applicable models, based on assumptions appropriate to a specific context, rather than to seek to develop universally applicable models. Customised models of this sort are most effectively delivered through a flexible decision support environment, which can facilitate the use of appropriate models for specific tasks and an appreciation of the strengths and weaknesses of different approaches, and enables managers to integrate the functionality delivered by a model into customised decision support tools.

Using the above ideas, the authors are attempting to develop implemented models from a set of context appropriate assumptions and a toolkit of methods for addressing those assumptions. NRM Tools (Walker & Johnson, 1996b) is a decision support toolkit that is designed to provide the flexibility of application required in practical decision support for integrated natural resource management (see Walker and Johnson, 1996a for details of the 'needs analysis' that underpinned the design of NRM Tools). NRM Tools provides the user with a 'task language' (essentially a high level programming language) with which to combine and recombine analytical functionality and data sources to meet the requirements associated with a particular task.

The analytical functionality made available through the task language can include quantitative models, qualitative or semi-quantitative knowledge (such as guidelines for best practice) implemented as knowledge-based systems (most familiar in the form of expert systems), algorithms for the analysis of spatial data and so on. This functionality can include existing software (implemented models for example) or analytical functionality developed specifically for integration into the toolkit. Given the essentially spatial nature of most natural resource management, a geographic information system (GIS) provides a core and integrating technology within the toolkit.

As one aspect of NRM Tools, integration of models for didactic, predictive, legislative or data acquisition purposes is achieved by utilising a standardised model framework to relate, access or modify existing models, or construct new ones. For the framework to fully cover the range of possible scenarios necessitates that it be formally exact; in fact, this requirements makes it possible to design models which bridge the gap between simple management support models and relatively complex "research" models in a well controlled manner.

This framework is achieved by regarding material export from a catchment as the sum of net material generation (eg erosion) at previous times, weighted according to the residence time distribution of the material within the catchment (see Barnes and Short, 1997). Specific model assumptions are then seen as allowing an approximation to either the generation rate, or the residence time distribution (which in general is non-stationary). The information content of available data determines the maximum level of complexity of the approximation, and potentially also uncertainty estimates. As further data becomes available, uncertainty estimates can be progressively refined, or simplifying assumptions relaxed to allow more sophisticated sub-models, as appropriate.

For example, consider the management question of the effect of clearing a particular area of land on average phosphorous loads delivered to the mouth of the catchment. This generic question is one which has been considered as part of a DSS being developed for use in the lower Herbert River catchment, in northern Queensland. Infrequent measurements of phosphorous concentrations in stream water are available, but continuous measurements of turbidity and stream height (discharge) have been made for some time at a few locations, and distributed historical rainfall data is available. Because the question concerns only the average phosphorous load, it is only necessary to consider changes in the generation rate of phosphorous. Conceptually, use of the available data requires a relationship between phosphorous loads and measured turbidities (turbidity becomes a surrogate for phosphorous); and also between changes in land use and turbidity generation, via hydrology.

This leads to a combined model of seven parameters relating land use change to phosphorous load, via a series of assumptions which are in accordance with existing catchment data, but may be relaxed or replaced as further data becomes available or needs require. Parameters are chosen so that they vary only slowly (if at all) with scale. All parameters have interpretations in terms of a simple conceptual model of the catchment system (eg characteristic velocity of quickflow), maximising the use of the model and predictions for learning. Each of these parameters can be determined from the available system data, and each group of at most two parameters is independently evaluated, so that the correlation between estimates is minimised. This maximises the power of the model to discriminate between differences in catchment behaviour.

In contrast to the uncertainties in the parameter values for current land use, which can be evaluated from existing data, dependence of some parameters on changed land use is relatively uncertain, and may require further specific data to yield acceptable uncertainties. Use of data from "similar" catchments may provide an indication of expected behaviour, but with unknown uncertainty (eg. use of USLE for prediction of mean turbidity from particular land uses).

Thus, by careful choice of model form and parameterisation, and by taking full account of the available data and intended use of the model, it is possible to retain flexibility and simplicity simultaneously, as required for decision support. Furthermore, this type of analysis of data and assumptions provides a firm basis for explanation of confidence and uncertainty in relation to model output. Where integrated with other analytical methods in a flexible toolkit environment (enhancing operational relevance), we argue that this approach allows a more rational integration of hydrological models into the decision-making processes than has previously been achieved.

6. REFERENCES

Barnes, C.J., Short, D.L. and Bonell, M. (1997). Modelling water, nutrient and sediment fluxes using catchment scale parameters. *Hydrochemistry* (Proceedings of the Rabat Symposium, April 1997) IAHS Publ. No. 244, pp. 195-205.

Davis, J.R. and T.F.N. Farley. (in press). CMSS: Policy analysis software for Catchment Managers. *Environmental Software*

Gross, P.R. and N. Levitt, N. (1994) *Higher Superstition: The academic left and its quarrels with science.* The John Hopkins Uni Press, Baltimore.

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

Panuska, J.C, I.D. Moore and L.A. Kramer. (1991). Terrain analysis: Integration into the agricultural nonpoint source (AGNPS) pollution model. *J. Soil and Water Conservation*, 46, pp. 59-64.

Rauscher, H.M. 1995 Natural resource decision support : Theory and Practice. *AI Applications* 9(3): pp 1 - 2.

Thomas Kuhn, (1963). *The Structure of Scientific Revolutions*, Chicago University Press, Chicago.

Tibor, T. (1996). *ISO 14000 : A guide to the new environmental standards.* Chigaco : Irwin Professional Publishers.

Walker, D.H. & Lowes, D. (1997). Natural Resource Management :Opportunities and challenges in the application of decision support systems. *AI Applications.* Vol. 11, No. 2, pp 41-51

Walker, D.H., Johnson, A.K.L. (1996a) Delivering flexible decision support for environmental management - a case study in integrated catchment management. *Australian Journal of Environmental Management* Volume 3, Number 3, pp 174 - 188

Walker, D.H., Johnson, A.K.L. (1996b) NRM Tools : a flexible decision support environment for integrated catchment management. *Environmental Software* Volume 11, Numbers 1-3, pp 19-25

Young, R.A., C.A. Onstad, D.D. Bosch and W.P. Anderson. (1989). AGNPS: A nonpoint-source pollution model for evaluating agricultural watersheds. *J. Soil and Water Conservation*, 44, pp. 168-173.