A Generalised Conceptual Framework for Integrated Assessment Modelling of Water Resource Management Issues

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Abstract: Nodal network approaches are a common framework for considering water allocation problems. In this type of model framework, a river basin is represented as a series of nodes, where nodes generally represent key points of extraction along the stream. Agricultural production and other water use decisions generally interact with the stream system in two ways: they can affect the generation of runoff and thus the volume of water reaching the stream; or, they may involve direct extraction or use of streamflow once it has reached the stream. This paper provides a generalised conceptual framework for considering these types of interactions and their representation in integrated water allocation models.
Keywords: water allocation, conceptual framework, integrated assessment, integrated water resources management

1 INTRODUCTION

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

Three recent projects conducted at the Australian National University have developed nodal network models for considering very different land activities, scales and management issues (see Jakeman and Letcher [2001]; Letcher et al. [in press]; Letcher and Jakeman [2003]; Gilmour et al. [under review]). Experiences gained in these projects have led to the development of a general framework for integrated assessment modelling of water allocation issues. This paper develops this framework and outlines several examples of the way in which it can be used to consider various activities and water related management options. Limitations of the current framework and avenues for future development are also discussed.

2 INTEGRATED ASSESSMENT

Integrated assessment is a holistic approach for assessing the impacts and trade-offs related to various land and water related management options. The need for integrated assessment of such issues has been well documented (see for example Letcher and Jakeman [2003]; Jakeman and Letcher [2003]).

In terms of water allocation, integrated assessment models must be able to consider a wide range of land use and management activities that impact on catchment yields. Aspects of the catchment system that must be represented include agricultural and other types of decision making that affect water use or rainfall-runoff generation (socio-economic decision making), the impacts of changed vegetation cover including forest area, farm dam capture and extractive use on the stream, issues of water availability and its impact on crop and livestock production, and the impacts of changed water and land management policy on households, farms and regional communities. The detail with which these system components are considered will depend on the scale at which the management questions are to be answered, the types of land and water use activities present in the catchment and the types of management options to be considered. Several common component models however can be considered.

2.1 Socio-economic decision and impact components

For the socio-economic sub system, two main components must be considered by the model. These are the decision-making component and the socio-economic impact component.

2.1.1 Decision Models

The decision-making component must represent the key land and water use and management decisions being made in the catchment. These may include agricultural production decisions, industrial and urban water use decisions as well as decisions to plant areas of the catchment to forestry or to capture runoff for productive purposes before it reaches the stream. The specific decisions to be simulated and the types of models used to represent these decisions will depend on the spatial and temporal scales at which these decisions are to be modelled as well as on the types of activities present in the catchment. For example, even where extractive uses such as irrigation direct from the stream are considered, this decision may be modelled differently depending on whether the decision is posed as a short-run decision, considering capital to be constrained, or a long-run decision where capital investment decisions are included in the model. Additionally for some issues a representative farm model, simulating decisions by an individual farm, may be used, whereas for larger scale studies, or studies where trade-offs between different industry users are to be considered, aggregated regional production models may be used. In either case, it is the relevant land and water use decisions that are being represented. Frequently used methods for simulating decisions include optimisation-based approaches, based on the assumption that individuals and firms act to maximise profits or utility, and decision tree approaches, where decisions are simulated using empirically derived ‘rules of thumb’.

In general two types of decisions may be made: those based on perfect knowledge of water and land availability; and, those made on the basis of uncertain expectations.

2.1.2 Impact Models

The second component of the socio-economic system that must be represented is the impact component. This component consists of the relevant social and economic impacts of changes in other system components. This may include impacts on farm profits and financial viability, impacts on the regional economy, and on individuals and communities. In some cases local impacts are aggregated and passed to a separate regional scale model (eg. an input-output model) to estimate second order impacts. Again, the scale and range of impacts to be considered dictates the type of modelling approach used.

2.2 Biophysical modelling components

Other aspects of the catchment system that must be represented are relevant biophysical system components. The biophysical components which must be considered will depend on the scale of modelling undertaken, the land use and management activities represented by the model and the types of policy scenarios to be considered. In all cases the hydrological component of the system must be represented in some way so that water allocation can be appropriately considered. The representation of this component must be made so that it has the appropriate sensitivity to various land use activities and policy options being considered. For example, if farm forestry is a land use option for the catchment, then the sensitivity of water yields to forest area must be represented. Croke and Jakeman [2001] provide a good overview of the limits to prediction in hydrology. Other components may include crop and livestock growth models, sensitive to the availability of both land and water and farm dam capture components. For the purposes of the general framework developed here land use activities are considered to be extractive (eg. irrigation from stream) or non-extractive (eg. farm forestry, farm dam capture) in their interaction with the stream.

3 GENERALISED FRAMEWORK

This generalised framework for integrated assessment modelling of water allocation options provides a generic conceptual model for a nodal network approach to considering water allocation. The form of this conceptual model differs on the basis of the types of decisions being made: those based on perfect knowledge of water and land availability; and, those made on the basis of uncertain expectations. Two types of productive uses are also considered. Extractive uses are those that impact on the stream system after rainfall-runoff has reached the stream. Non-extractive uses are considered to be those that influence rainfall-runoff generation before it reaches the stream (revegetation, capture of rainfall-runoff in on-farm storages for livestock or irrigation uses).

The Biophysical Modelling Component (BMC) consists of crop and hydrological modelling components. Where land use activities are extractive, a 'policy filter' is generally required to translate streamflow into available extraction limits, and to translate lumped extractions to extraction on the same time scale as used by the hydrological component. When land use activities are non-extractive, the hydrological component must have the appropriate sensitivities to these non-extractive uses.

3.1 Perfect knowledge based decisions

Where decisions are simulated under conditions of perfect knowledge, the decision and impact components are represented by a single model component. This is because decisions are made with full knowledge of the impacts they will incur on the social and economic subsystems, and are usually taken into account in the decision simulation. That is, an agricultural production decision is generally made to trade-off the economic and social impacts on the production unit (household or farm).

For perfect knowledge based decisions, regardless of whether the land use is extractive or non-extractive the general conceptual framework is shown in Figure 1.

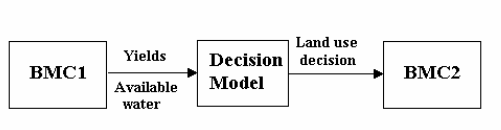

Figure 1. Conceptual framework for decisions based on perfect knowledge

In this case, BMC1 and BMC2 may not contain the same models. BMC2 must contain a hydrological model that is sensitive to changes in the land use activity considered by the decision model. BMC1 may contain only very simple models of crop/activity yield and climate impact of available water. For extractive uses this will be a hydrological model simulating pre-extraction flows, whereas for non-extractive uses this may be a filter on rainfall or evaporation to determine dam capture, or forest yields. In any case BMC1 generally represents the biophysical systems knowledge assumed to be known by the decision maker before making the decision. Several examples of the use of this framework for considering extractive and non-extractive activities are given in the next sections.

3.1.1 Non-extractive land use activities

One possible non-extractive land use activity that has impacts on the availability of water in-stream is forestry. Where forestry decisions are made under the assumption of perfect knowledge the conceptual framework may be applied to produce a model integration structure as shown in Figure 2.

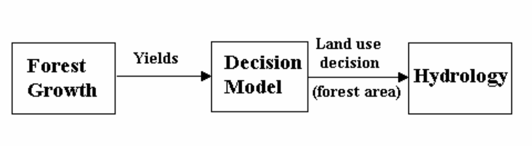

Figure 2. Application of framework for perfect knowledge, forestry activities

In this case BMC1 simulates forest growth (and thus yields). The level of complexity of this component is variable. It may range in complexity from a full forest growth simulation model to a simple empirical model to a look-up table approach. This forest growth component (ie. BMC1) passes forest yields to the decision model. The decision model then links to BMC2, a hydrological model, using the land use decision, or chosen forest area. This hydrological component must be sensitive to changes in forest area.

Another example of a non-extractive land use that has impacts on streamflow yield is the use of farm dams to capture runoff for activities such as viticulture. The integrative framework that results for this activity is illustrated in Figure 3.

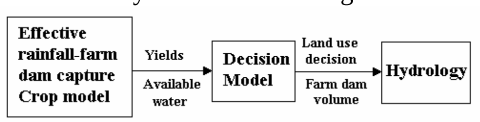

Figure 3. Application of framework for perfect knowledge, runoff capture activities

In this case BMC1 consists of a component to estimate the capture of runoff in farm dams for a given climatic series and a crop growth component. The estimate of farm dam capture may be on a per ha or ML of storage basis where capacity is a decision, or for total capacity where capacity is a constraint to decision making. Links between BMC1 and the decision model comes through simulated crop yields and water available in farm dams for irrigation purposes. BMC2 consists of a hydrological modelling component, which must be sensitive to changes in farm dam capacity in the catchment. BMC2 is integrated using the total volume of farm dam capacity and the area based land use decision, which are outputs of the decision component.

3.1.2 Extractive land use activities

Application of the conceptual framework for considering extractive activities, such as the production of irrigated crops using water extracted from streams results in the integrative framework shown in Figure 4.

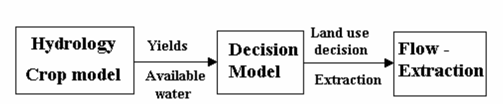

Figure 4. Application of framework for perfect knowledge, extractive activities

In this case, BMC1 consists of both hydrological and crop model components. A policy filter, which models extraction policy rules, must be used to determine water available for extraction on an appropriate time step. BMC1 is linked to the decision model by yields (or productivity) and available water. BMC2 is then a second hydrological component that removes extracted water from 'natural' flow. The decision model integrates with BMC2 through the extraction implied by the area based land use decision.

3.2 Expectations based decision making

Where decisions are assumed to be based on uncertain expectations, a separate decision model and impact model need to be used because the actual impact can only be determined or modelled after the land use decision has been made. Regardless of whether or not the land use is extractive or non-extractive, the general framework for integration is shown in Figure 5.

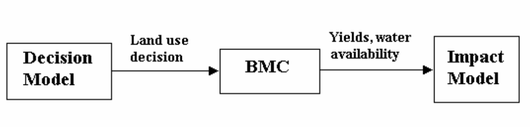

Figure 5. Conceptual framework for decisions based on uncertain expectations

Several examples of the application of this conceptual framework to various activities are given in the next sections.

3.2.1 Non-extractive land use activities

Application of the conceptual framework to forestry plantation would result in model integration of the form shown in Figure 6.

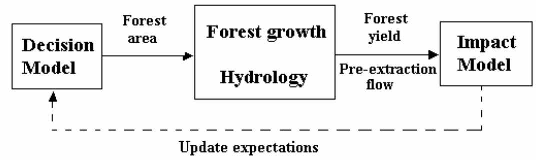

Figure 6. Application of expectations based framework, forestry activities

In this case the BMC consists of a hydrological modelling component, which must be sensitive to changes in forest area, and a forest growth simulation component, which may be as simple as a look up table of forest yields. In this case the link between the decision model and the BMC is the forest area, which is an output of the socio-economic decision. The BMC then passes the yield of forest products and the pre-extraction (often referred to as 'natural') streamflow to the impact model.

Application of the conceptual framework to expectations based decisions on activities involving runoff capture in farm dams results in model integration as shown in Figure 7.

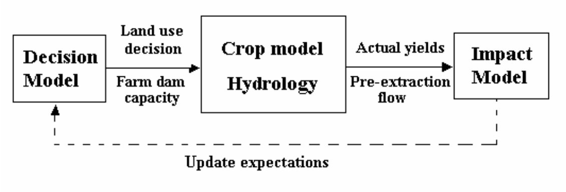

Figure 7. Application of expectations based framework, runoff capture

In this case the hydrology must be sensitive to changes in the capacity of farm dams for capturing runoff. Crop yields must also be sensitive to the availability of water in farm dams for irrigation. The link between the decision model and the BMC is again the area based land use decision and the corresponding farm dams capacity. Where the farm dam capacity is treated as a constraint rather than a decision variable then this capacity is a fixed input to the BMC. It is not produced as an output of the decision model in this case.

3.2.2 Extractive land use activities

If the land use activity considered is extractive, then the BMC will contain a hydrological modelling component and may contain a crop model (this may be simple/empirical crop model, or a simple look-up table of relevant crop yields and water use). The integrated model structure using the conceptual framework is shown in Figure 8.

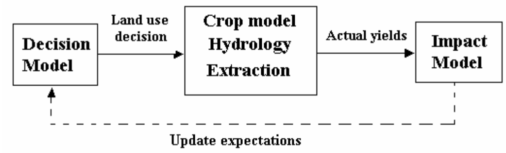

Figure 8. Application of expectations based framework, extractive activities

As before the link between the decision model and the BMC is the area based land use decision. The BMC then links to the impact model through simulated yields from the crop modelling component. In this case extraction and water allocation between alternative crops for the node must be handled using a water allocation module within the BMC, based on a set of predefined prioritisation rules. This is different from the extractive framework under perfect knowledge assumptions (see Section 3.1.2), where water allocation decisions internal to the node were handled by the decision model.

4 MULTIPLE ACTIVITIES AND OTHER INTEGRATION CONSIDERATIONS

In many cases the integrated assessment will be expected to consider a range of extractive and non-extractive land uses at a single node. In this case the concept of a land modelling unit (LMU) may be used to disaggregate decision making at the node.

4.1 Land Modelling Units

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

4.2 Use of the conceptual framework for considering multiple LMU at a node

Consider a situation where two separate sets of policy interventions are likely to impact on the stream system: areas of the upper catchment currently under a grazing system are being considered for reforestation to manage salinity problems in the catchment; and, access to irrigation water extracted direct from the stream is to be changed to manage environmental flow outcomes. Figure 9 demonstrates an example of the break down of this type of catchment into two separate LMU types based on current land use and its interaction with these two policies. LMU 1 correponds to areas currently under pasture or forest and is directly affected by the first policy. LMU 2 corresponds to current and potentially irrigated areas of the catchment, which are areas affected by the second policy. The node is placed at the subcatchment outlet.

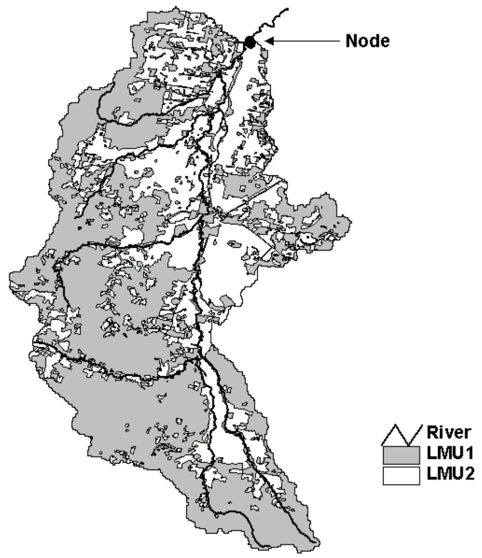

Figure 9. Example LMU break down of catchment

A conceptual framework for modelling this set of issues and activities, where it is assumed that farmers have perfect knowledge, would then be as shown in Figure 10.

The generalised conceptual framework is implemented first for LMU 1 since this affects non-extractive activities. The BMC components for this LMU include a forest growth model and a rainfall-runoff component where effective rainfall is dependent on forest area. The implementation for LMU 2 then links through this rainfall runoff component and a crop modelling component to the decision model for LMU 2. The impact of extractions on streamflow is then considered in a third BMC.

Figure 11 demonstrates the conceptual modelling framework for this problem where both sets of decisions are assumed to be expectations based.

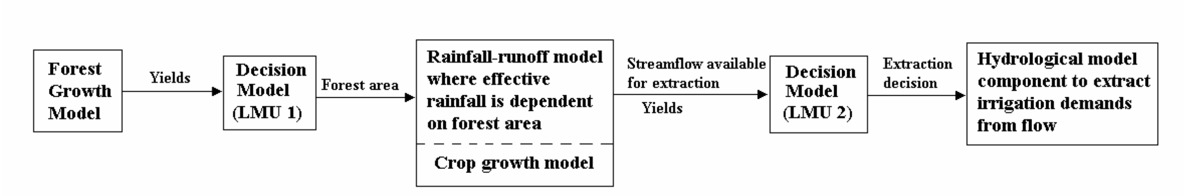

Figure 10. Conceptual framework for multiple LMU under perfect knowledge assumption

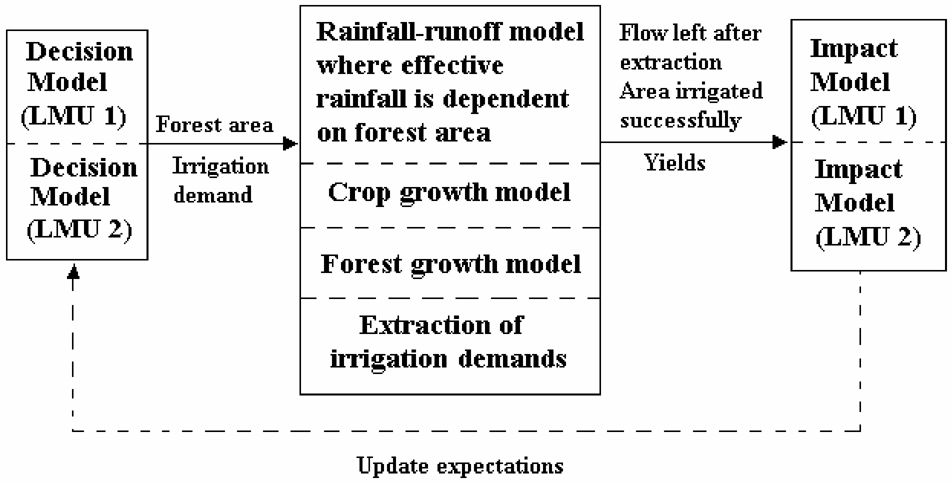

Figure 11. Conceptual framework for multiple LMU under uncertain expectations

This figure demonstrates that both decision models (ie. for LMU 1 and 2) are able to be run concurrently since expectations are all that is required for the decision. These models then pass forest area and irrigation demands to the BMC. This component includes a rainfall-runoff where effective rainfall is dependent on forest area, crop and forest growth models and extraction of actual irrigation demands from streamflow. The area successfully irrigated, crop and forest growth and flow left after extraction are then passed to the impact model to consider the impact of actual values of these on the decision-maker. This information is then used to update expectations for the next set of decisions.

5 DISCUSSION AND CONCLUSIONS

The conceptual integrative framework described in this paper has been successfully applied to consider water quantity based issues such as water allocation, runoff capture and the impacts of forestry plantation on flows (see Jakeman and Letcher [2003] for examples of its application). It should be able to be adapted for a range of land and water based management issues, including water quality and ecological management issues relatively easily. It is expected that these modifications would be made primarily during definition of the LMU for land based activities and impacts, and during definition of nodes for in-stream impacts.

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