Sensitivity Analysis Of An Integrated Model For Assessing Land And Water Policy Options

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Abstract: This paper outlines results from carrying out a sensitivity analysis on an integrated model. The model was developed to examine water policy and land use change options in the Yass River catchment, NSW. The integrated model has three components consisting of policy, hydrological and agricultural production system models. The sensitivity analysis involved running variables in the model over a broad range of values to examine the response of model outputs. For ease of interpretation, three indicators were used to examine the model output. They were the number of zero flow days, the median of non-zero flows and agricultural profit. The analysis shows that the model is sensitive to changes in inputs to all component models. The sensitivity of the model varies depending on whether the input selected has a direct or indirect effect on other system components. Results are presented to illustrate the response of the integrated model when assessing the land and water policy options selected for analysis.

Keywords: *Sensitivity Analysis; Water Resources; Integrated Modelling; Catchment scale*

1. INTRODUCTION

In response to problems in Australian catchments, the past decade in Australian water resources management has been largely devoted to the evolution of a complex system of water management and allocation rules to meet the needs of all users. Arguably, the largest step in adjusting the way in which water is used has been the inclusion of the environment as a legitimate user of water. An integrated approach to water management including acknowledgment of the use of water within the social, ecological and physical constraints of the catchment system is the major change to managing water resources.

1.1. Need for an Integrated Model

Lack of scientific information, both biophysical and socio-economic, has been one barrier to developing a set of successful management strategies within the Water Reform Process. Where comprehensive scientific studies have taken place to identify the water needs of the physical environment, often the long term economic impacts on water users are unknown. Secondly, there is currently little understanding of both the magnitude and nature of socio-economic-hydrological-environment interactions.

Many frameworks and studies have been proposed for investigating the biophysical impacts of allocating water in a certain way (see for example Banens *et al.,* 1996; Davis and Young, 1998; and Young *et al.,* 1998). Similarly, a plethora of studies have investigated economically optimal water allocation options (see for example Brennan and Scoccimarro, 1999; Dudley, 1998; and Hall *et al.,* 1994). However, how users of water impact upon each other and the water resource through economic decisions is a basic question that has not been answered in the majority of catchments. Developing a successful management strategy is further hindered by the lack of conceptual frameworks available to document system interactions and aid the decision making process.

Jakeman and Letcher (2001) propose the use of integrated assessment frameworks in catchments as a way forward and illustrate this with examples. Questions that need to be answered focus around identifying and characterising the nature of economic-hydrological-environment interactions. The Water Reform Process requires a range of integrated tools and techniques to implement a new set of water allocation rules and answer such questions.

2. INTEGRATED MODEL DESCRIPTION

The primary aim of this study has been to develop an approach for assessing a range of water allocation rules and other natural resource management policies at the catchment scale. In this study, the socio-economic component is defined by the decisions of agricultural production systems. The integrated model examines the impact of agricultural production decisions on the hydrological system and vice-versa as a result of implementing three main policy options.

2.1. Policy Options in Yass Catchment

The approach was developed and tested in the Yass river catchment in the Upper Murrumbidgee. This is largely a dryland, unregulated system with limited areas of irrigated production. Water based licenses have recently been converted from an area based allocation to a volume. The catchment suffers from over-extraction of streamflow and land clearing. Consequently, the catchment has a very severe salinity problem in both its land and water systems. In addition, farm dam development has been prolific due to the requirement of rain-fed dryland activities such as grazing and recently introduced intensive land uses such as viticulture. The policy options in the catchment are:

1. Salinity Management Policy
2. Farm Dams Policy
3. Volumetric Conversions Policy

2.2. The Agricultural Production System Modelling Hierarchy

The integrated modelling approach developed operates at three modelling scales. The basic unit of the hierarchy is the Activity, followed by Land Management Units and finally Nodes. This hierarchy was developed to facilitate integration between different system processes (principally those of the hydrological and agricultural production systems) at each scale. Activities, being the lowest level in the modelling hierarchy, are contained within Land Management Units. Land Management Units are contained within nodal areas, which are the residual subcatchment areas upstream of Nodes.

At the Activity level, economic return per hectare of each agricultural production activity is calculated. At the Land Management Unit level, this information is used to make decisions as to area devoted to each land use activity. At the Node level, system response is calculated as a result of the decisions made at the Land Management Unit level. Integration between agricultural production components and the hydrological system is also undertaken at the nodal scale. Integration of the policy options and the agricultural production system hierarchy is shown in Figure1. There were four nodes, twelve LMUs and six activities in the integrated model of Yass catchment (see Gilmour, 2003).

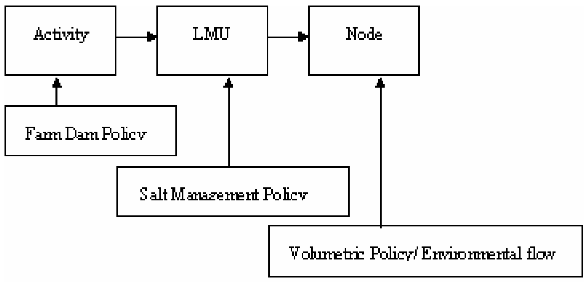

Figure 1. Integration of policy options with the model hierarchy.

2.3. Integration with the Hydrological Models

Integration at the node can be considered in a generic way by grouping LMUs as pre-extractive and extractive types. Figure 2 shows the interaction between pre-extractive and extractive LMUs at the Node level in the model hierarchy. A pre-extractive LMUs may be a dryland or supplementary-irrigation LMU. Total forest area and the volume of farm dams are summed over all pre-extractive LMU at the node. This aggregated information is passed to the hydrology model where the change in runoff and hence streamflow at the Node is calculated for the whole forested area in the LMU.

For extractive LMUs, the policy model calculates the annual extraction limit given licence volumes and the daily flow extraction rules. The extractive model allocates annual extractions over each day for a 20-year simulation. This results in streamflow minus extractions being calculated at the node. Extractions are also passed to downstream nodes.

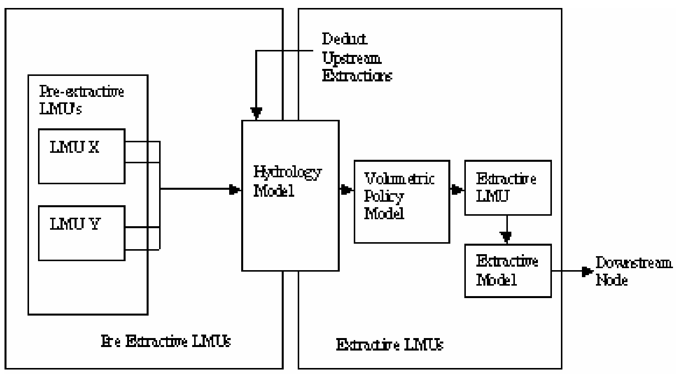

Figure 2. Conceptual framework for model integration at a node.

3. MODEL OUTPUT AND SENSITIVITY TESTING

The integrated model output contains information on both hydrological and agricultural production system model components. The output is complex, ranging from the areas devoted to various activities, streamflow, extractions, profit and farm dam volumes. To reduce the complexity of model output and provide ease of interpretation, a series of indicators were used to assess model sensitivity. In the first instance, a Base Case scenario was run. The Base Case is the catchment system in its current policy state (at the time of model development).

3.1. Indicators used to interpret model output and variables tested

In order to apply consistency in testing both the production model and the hydrology variables, the following three indicators were selected to test the model at each Node:

1.Total nodal profit ($)
2. Median of non-zero flows (Megalitres)
3. Number of zero flow days

Table 1 shows the model variables that were subject to sensitivity testing, including the three reported in this paper. It identifies which variables were tested and the variables that were not tested but could be in future work.

Table 1. Variables tested and variables that could be tested from the integrated model components.

Variable Value	Test
Agricultural Production Model Component	
Maximum area of viticulture	Yes
Maximum area of irrigable land	Yes
Yield for viticulture	No
Yield for irrigable activities	No
Yield for forestry	No
Grazing yield variability with rainfall	No
Prices for crop yields	No
Water use of viticulture and irrigable crops	No
Hydrological Model Component	
Threshold for catchment moisture	No
Available daily rainfall	Yes
Evaporative loss from farm dams	Yes
Area required to drain 1 ML of water	No
Runoff coefficient	Yes
Policy Scenarios	
Maximum allowable volume of farm dams	Yes
Commence to pump rules	Yes
Maximum pump capacity of irrigators	No
Daily Extraction entitlement	Yes
Annual Licence Allocation	Yes
Area of land devoted to farm forestry	Yes

The maximum area devoted to each activity was tested from the agricultural production modelling component. In addition, the land made available to viticulture activities was calculated using land use maps and slope to identify areas. The sensitivity analysis varies the potential land available to viticulture and examines the effects on the results at each Node. Similarly, area devoted to irrigation was also tested given that the same land use data was utilised to identify all areas of potential for irrigable activities.

Sensitivity testing was carried out on all three policy options to ascertain how appropriate the integrated modelling approach was for examining scenarios specifically aimed at the Farm Dams Policy, Volumetric Conversions Policy and Salinity Management Policy options.

For each of the variables identified in Table 1, a percentage variation from the Base Case was applied. The sensitivity analysis was carried out by changing the value of the variable over several (up to ten) increments. The change occurred in increments, usually both above and below the variable identified in the Base Case. The measure of sensitivity, given as a percentage is:

$$\frac{\text{scenario indicator value} - \text{base case indicator value}}{\text{base case indicator value}} \bullet 100$$

All other model variables remained as per the Base Case model, that is only one variable at a time was changed to examine the effect on the outputs. The simulations were carried out over 20 years.

4. RESULTS

For succinctness, three results are presented in this paper. The examples illustrate variables that were highly sensitive to changes from the Base Case value and those that were less sensitive. The first two examples demonstrate the difference in model sensitivity to variables with a direct impact on other system components compared to those with an indirect impact. The third example shows how the sensitivity analysis is useful in defining the model limitations in terms of strength of the integration between model components.

4.1. Policy Model Component: Changes in the area of farm forestry

To test the variable responsible for implementation of the Salinity Management Policy Option through forestry plantation in the integrated model, the area of farm forestry was changed by 10% increments. Normally the percentage change would be measured from the Base Case for consistency in testing. Given that there was no forestry planted under the Base Case model, it was decided to vary the area of the catchment planted to forestry from 10% of the total catchment area to 80% of the catchment area available for forestry plantation.

Sensitivity of the three indicators to the area devoted to farm forestry was tested with respect to the area belonging to each node. The number of zero flow days did not change. This could be expected because changes in runoff as a result of plantation establishment were not significant. The number of zero flows could be expected to increase if the total change in runoff was larger. The modelled runoff was not highly sensitive to changes in plantation cover. At most, a 5.3% change in the median of non-zero flow occurred. This is not enough to reduce small streamflow events to zero streamflow events in the integrated model.

Figure 3 shows the change in total nodal profit as a result of implementing a given salinity management option (farm forestry). The greatest economic impact occurs for the area belonging to Node 4. There is a 92% reduction in profit where the area devoted to forestry is 80% of the catchment area. Nodes 1 and 2 also experience a decrease in profit up to 60% when the land use change to forestry occurs. Node 3 has the second largest impact because viticulture is taken out of production and replaced with forestry. Viticulture is a 'value added' agricultural activity with a high per hectare economic return relative to other activities. It could be expected that replacing this activity with forestry would result in a larger reduction in profit compared to other nodes that do not contain the activity.

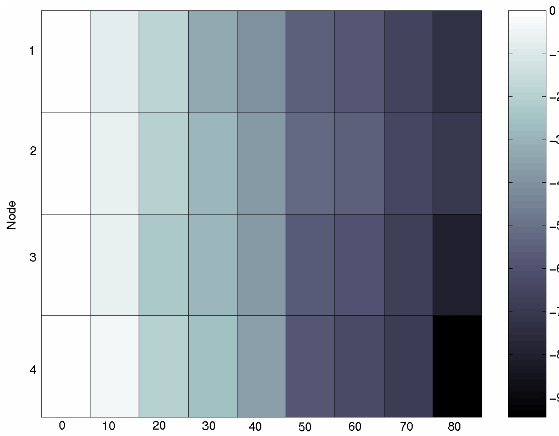

Figure 3. Model sensitivity of nodal profit to percentage of the catchment under forest cover. Base Case shown as 0 on the horizontal axis.

4.2. The Hydrological Model Component: Testing Rainfall Reduction

Four climate scenarios were run through the integrated model to examine the sensitivity of the three indicators to a reduction in daily rainfall. The model was tested for reductions of 5%, 10%, 15% and 20% in rainfall. Profit and the median of non-zero flows were sensitive to the scenarios. The number of zero flow days was not sensitive.

A rainfall change has several points (direct and indirect) of potential impact in the model. A direct impact results from the use of daily rainfall as an input to the hydrology model, determining available streamflow, runoff and the volume of water available in farm dams. A second direct impact is the use of daily rainfall to determine the yield of cattle grazing activities. An indirect impact and point of integration between rainfall and the agricultural production system is the loss in runoff and hence available streamflow for in-stream irrigated activities as the fraction of the catchment given over to forestry production increases.

Figure 4 shows the change in profit as a result of reducing the daily rainfall. The result indicates that a linear reduction in profit occurs with each 5% reduction in rainfall. A decrease in profit of approximately 2% occurs across the nodal network with each incremental reduction in rainfall. Nodes 1,3 and 4 have the largest decrease in profit of approximately 6% where rainfall is reduced by 20%. This could be expected because of the large area of land devoted to dryland activities at this node. The reduction is not as great at Node 2 because of the larger area devoted to irrigated activities that rely on an in-stream water supply for agricultural production.

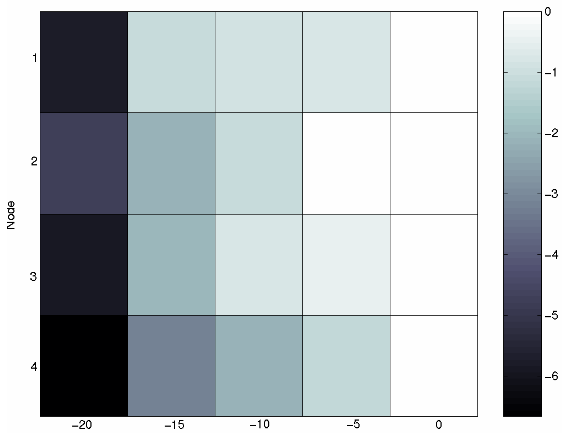

Figure 4. Model sensitivity of profit to percentage reductions in daily rainfall. Base Case value is located at 0 on the horizontal axis.

Figure 5 shows the resulting change in the median of non-zero flows. A 5% reduction in rainfall reduces the median of non-zero flows by approximately 5% across all nodes, but is slightly less at Node 4. This is to be expected as a reduction in rainfall will reduce streamflow. A threshold effect occurs where the reduction in rainfall is 20% of the Base Case. In this case, the reduction in the indicator increases to approximately 25% in contrast to a 12% reduction in profit when rainfall is reduced to 15%.

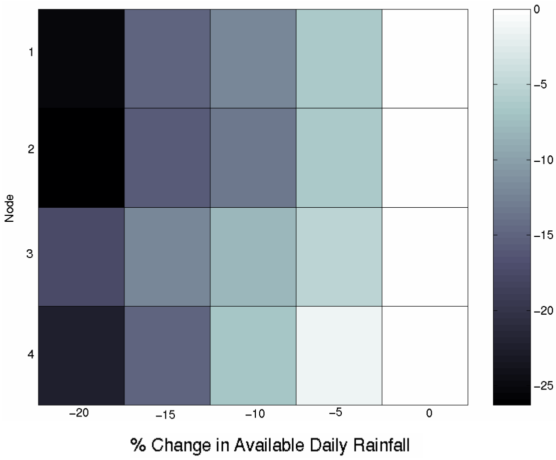

Figure 5. Model sensitivity of median of non-zero flows to percentage reductions in daily rainfall. Base Case value is located at 0 on the horizontal axis.

A reduction in both the agricultural production indicator, profit, and the hydrology indicator, the median of non-zero flows, occurred for the model scenarios. Streamflow is dependent on rainfall. The viability of dryland and viticulture activities depends on rainfall, for pasture production and farm dam capture respectively. Therefore a reduction in profit as rainfall decreases is consistent with the conceptualisation of the integrated model, and with the underlying system.

4.3. Model Sensitivity to The Farm Dams Policy: Allowable Runoff Capture of Farm Dams

The sensitivity of the model to changes in rainfall volume captured in dams was tested by variation from the Base Case value of 30%, which was considered to be the actual capture (see Schreider *et al.*, 2002). The indicators, profit and median of non-zero flows, were sensitive to the scenarios. The number of zero flow days was not sensitive.

Model sensitivity of profit varied across the four nodes as indicated by Figure 6. Variation in the allowable capture volume has a direct impact on the viticulture activity in that it controls the volume of water captured in farm dams and hence used by supplementary irrigators to support the viticulture enterprise.

Node 3 was most sensitive to changes in this variable, resulting in a 28% change in profit for the scenarios run. Nodes 1 and 2 experienced a 20% and 26% increase in profit respectively over the grid sample. Node 4 showed the least sensitivity to the profit indicator as its area contains a relatively small amount of land that is allocated to viticulture. In contrast, Nodes 1, 2 and 3 contain viticulture as well as a smaller area of land devoted to irrigated activities. Node 3 has the largest change in profit as it has the largest area devoted to viticulture. Hence, it is reasonable to expect that changing the runoff capture to farm dams would have the greatest impact at Node 3.

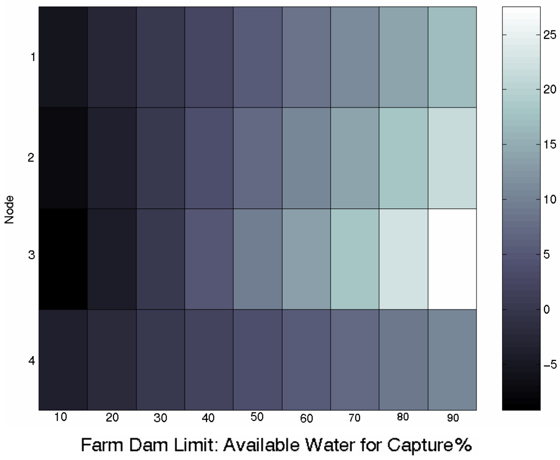

Figure 6. Model sensitivity of profit to percentage changes in allowable runoff capture for storage in farm dams.

Given that this variable controls the volume of water captured in farm dams, it would be reasonable to expect a change in runoff to the stream and a change in the hydrology indicators. Changing the variable has no impact on the number of zero flow days. Figure 7 shows the direction of change in the median of non-zero flows as a result of increasing the volume of farm dam capture across a sample grid of 10% increments.

The indicator is less sensitive than other variables previously tested. At Node 1 an initial change from capturing 40% to 50% of the Base Case runoff results in a slight decrease in the median of non-zero flows. Across all nodes, the change in the median of non-zero flow is small, resulting in a 0.02% change at Node 1 and incremental changes at Node 2, averaging just -0.013% for each grid step. Nodes 3 and 4 show similar model behaviour. These changes are much smaller than the comparative impacts on profit. This is because the impact on flows is indirect, filtered through much of the system, whereas the impact on production is a direct impact.

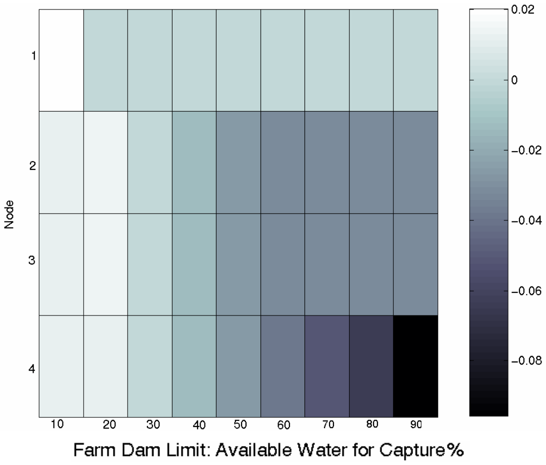

Figure 7. Model sensitivity of median of non-zero flows to percentage changes in allowable runoff capture for storage in farm dams.

5. DISCUSSION AND CONCLUSIONS

The sensitivity analysis carried out has been useful in highlighting the consistency of the model behaviour with respect to the integrated model conceptualisation. The sensitivity analysis revealed that for a selected policy option, a large magnitude impact was observed on activities that were directly affected by a change. This was seen in the large change in profit where land was devoted to forestry under a Salinity Management option and change in viticulture profit where the Farm Dams Policy was imposed. In addition to showing the consistency of model behaviour through direction of change, the results also support the behaviour of the model as being consistent with the model conceptualisation shown in Figures 1 and 2.

The usefulness of the integrated model is its ability to decipher impact that should be direct and that which is indirect. For instance, changes in runoff should have a smaller impact upon irrigated activities than that of viticulture that sources its water from runoff only. However, future work could examine the exact magnitude of the direct and indirect impacts to improve model performance. To date, the magnitude of change has been assessed from the perspective of what would be conceptually plausible. This work could also be extended to test individual model components.

6. REFERENCES

Banens, B., Lovett, S., and Young, B. (1996) The Environmental Flows Decision Support Program. Natural Resources Management Strategy Project No. R 6066. Murray Darling Basin Commission, Canberra

Brennan, D., and Scoccimarro, M. (1999) Australian Water markets. *The Australian Journal of Agriculture and Resource Economics*, 43(1). March 1999. Blackwell Publishers.

Dudley, N.J. (1998) Volume Sharing of Reservoir water. *Water Resources Research*, 24(5): 641-648.

Davis, J.R., and Young, W.J., (1998) A Decision Support System For Planning Environmental Flow Allocations, In D.P Loucks (ed). Restoration of Degraded Rivers: Challenges, Issues and Experiences, pp 357-376. Kluwer Academic Publishers. Netherlands.

Gilmour, J.K. (2003) 'An Integrated Modelling Approach for Assessing Land and Water Policy Option'. Unpublished PhD thesis. Centre for Resource and Environmental Studies, The Australian National University.

Hall., N, Poulter, D., and Curtotti, R. (1994) ABARE Model of Irrigation Farming in the Southern Murray-Darling Basin. ABARE Research Report 94.4. Australian Bureau of Agricultural and Resource Economics, Canberra.

Jakeman, A.J., and Letcher, R.A. Integrated assessment and information systems for catchment management. In F. Ghassemi *et al*., (eds), Proceedings of the International Congress on Modelling and Simulation, MODSIM 2001, Australian National University, Canberra, MSSANZ Inc., Vol 1, pp 31-42.

Schreider, S,Yu., Jakeman, A.J., Letcher, R.A, Nathan, R.J, Neal, B.P and Beavis, S.G. (2002) Detecting changes in streamflow response to changes in non-climatic conditions: farm dam development in the Murray-Darling basin, Australia. *Journal of Hydrology*, 262: 84-98.

Young, W.J., Booty, W.G., Cuddy, S.M., Farley, T.F., Lam, D.C., and Whigham, P.A. (1998) Ecological and Environmental Flow Regimes Using Decision Support Software. CSIRO Land and Water Report, Canberra.