Simulating Irrigation Water Management Under Hydroclimatic Uncertainty

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EXTENDED ABSTRACT

The past decade has seen great change in the institutional environment for water management. The COAG water reform framework (agreed to in 1994 by the Federal and State and Territory governments) is based around several key principles aimed at increasing water use efficiency:

- Property rights reform to clarify rights to water, including rights for the environment.
- Pricing reform to ensure users are charged the true cost of water.
- The promotion of water markets.

Reform has thrown up new challenges for the water authorities, which attempt to meet such diverse goals as maximizing water deliveries (for farmers, the customers, and for water authorities' own profitability), maintaining longer term security of supply, meeting environmental flow targets, and complying with other limits on use. Modelling capability can greatly aid the planning process.

The extent of feedback between the hydrological system and the irrigation sector calls for an integrated economic-hydrologic framework: a realistic representation of the hydrological system, incorporating the stochastic nature of inflows and the current operational rules, and economic modelling which helps understand how irrigators may manage their water.

One of the key aspects bearing on farmer water management is the uncertainty inherent in all of the basic parameters. This paper describes an integrated economic-hydrologic framework which has been set up to assess how irrigator behaviour under uncertainty might affect the outcomes of water reforms in the Goulburn system in northern Victoria.

Regional 'farmers' are represented by discrete stochastic programs, linked by a water market and the water storage and delivery system. There are twenty-six farmers in total, who make decisions about irrigation and water trading at the start of each season subject to uncertainty in crop water demands, irrigation water allocations and the opportunity cost of water (temporary water market prices). It is assumed that all trade goes through a water exchange.

The hydrology is modelled by the Goulburn Simulation Model, well established in modelling of this type.

To implement a discrete stochastic program, uncertainty must be encapsulated in a small number of possible states, and a probability of occurring associated with each. Each season is split into a 'wet' versus a 'dry' state, and allocations split into a 'high' versus a 'low' level for the year. As a first-cut, beliefs about the probability of each state of nature are assumed to match historical relative frequency, and only risk neutrality is modelled.

Although farmers are given the freedom to choose a different strategy for each state of nature, the simulated plans are relatively simple: mostly, farmers plan to irrigate the same areas regardless of seasonal conditions; or they may, for example, have one plan if spring is wet and another if spring is dry.

Plans formed at the beginning of spring are usually followed. The most common reason for a change in plan is failing to buy water. The further along in the year, the more farmers have invested in a particular plan, and a dramatic change in circumstances is required to change the optimal plan.

These results are based on one set of assumptions about states of nature, belief formation and attitudes to risk. Future work will conduct sensitivity analyses on these assumptions.

1. INTRODUCTION

The past decade has seen great change in the institutional environment for water management. It is now mainstream in policy documents to regard water as a scarce and precious resource, requiring careful management to balance economic, environmental and social values, and indeed, preserve our quality of life (DSE 2004).

Recognition of limits to use has seen a drive for efficiency. The COAG water reform framework (agreed to in 1994 by the Federal and State and Territory governments) is based around several key principles to increase water use efficiency:

- Property rights reform to clarify rights to water, including rights for the environment.
- Pricing reform to ensure users are charged the true cost of water.
- The promotion of water markets.

Water markets have been championed as a means of improving efficiency, particularly in irrigation, as they reveal the opportunity cost of water, and encourage the resource to move to higher valued uses. In the short run, temporary trade allows water to move in response to variability in availability of water and crop water requirements. In the long run, permanent water trade is a facilitator of structural change.

Reforms have thrown up new challenges for the water authorities charged with managing the whole system:

- Giving water a clear and realisable value means that more water may be used in total, impacting on security of supply, and/or compliance with any limits on use[1].
- Having entitlements to water change hands means that it may be called for in different places and at different times, with potential impacts on the ability of the storage and delivery infrastructure to provide water as required by irrigators.

These are serious operational issues. While opportunity cropping is common in New South Wales for example, northern Victorian industries such as horticulture and dairy require secure water supplies. Bottlenecks in the water delivery system can have grave consequences for farmers at critical watering times through the year.

In turn, changes in security of supply and chances of water being delivered when it is really needed are sure to influence irrigator behaviour.

The extent of feedback between the hydrological system and the irrigation sector means an integrated economic-hydrologic framework is essential for gauging possible impacts of policy changes. An integrated framework requires a realistic representation of the hydrological system, incorporating the stochastic nature of inflows and the current operational rules, and economic modelling which helps understand how irrigators may manage their water.

One of the key aspects bearing on farmer water management is the uncertainty inherent in all of the basic parameters. Farmers make decisions about irrigation and water trading without knowing how much water they will have access to; how much water their crops will require; and the opportunity cost of water (temporary water market prices). An assessment of how uncertainty is characterized, how beliefs are formed and attitudes to risk is warranted.

This paper describes an integrated economic-hydrologic framework which has been set up to assess how irrigator behaviour under uncertainty might affect the outcomes of water reforms. The hydrology is modelled by the Goulburn Simulation Model, well established in modelling of this type (Section 3). Regional 'farmers' are represented by discrete stochastic programs, linked by a water market and the water storage and delivery system.

The paper first describes the setting for the research, the Goulburn system. Section 3 sets out the integrated modelling framework, while Section 4 concentrates on the economic component. Some results are presented in Section 5, and then conclusions about the current work and future extensions are discussed.

2. THE GOULBURN SYSTEM

The Goulburn system in northern Victoria is one of the major irrigation systems in Australia. The major storage is Lake Eildon. On release, water flows down the Goulburn river to the Goulburn weir, before most is diverted into the Western Waranga Channel or the East Channel. The Loddon and Campaspe rivers and storages at their bases also form part of the system. These three rivers join the Murray, and thus the system is part of the Murray-Darling Basin (Figure 1).

[1] For example, the Murray-Darling Basin Cap, introduced in 1995 to limit Basin diversions to 1993-94 levels of development: that is, the volume of water that would have been used in 1993-94 if the current seasonal conditions had prevailed.

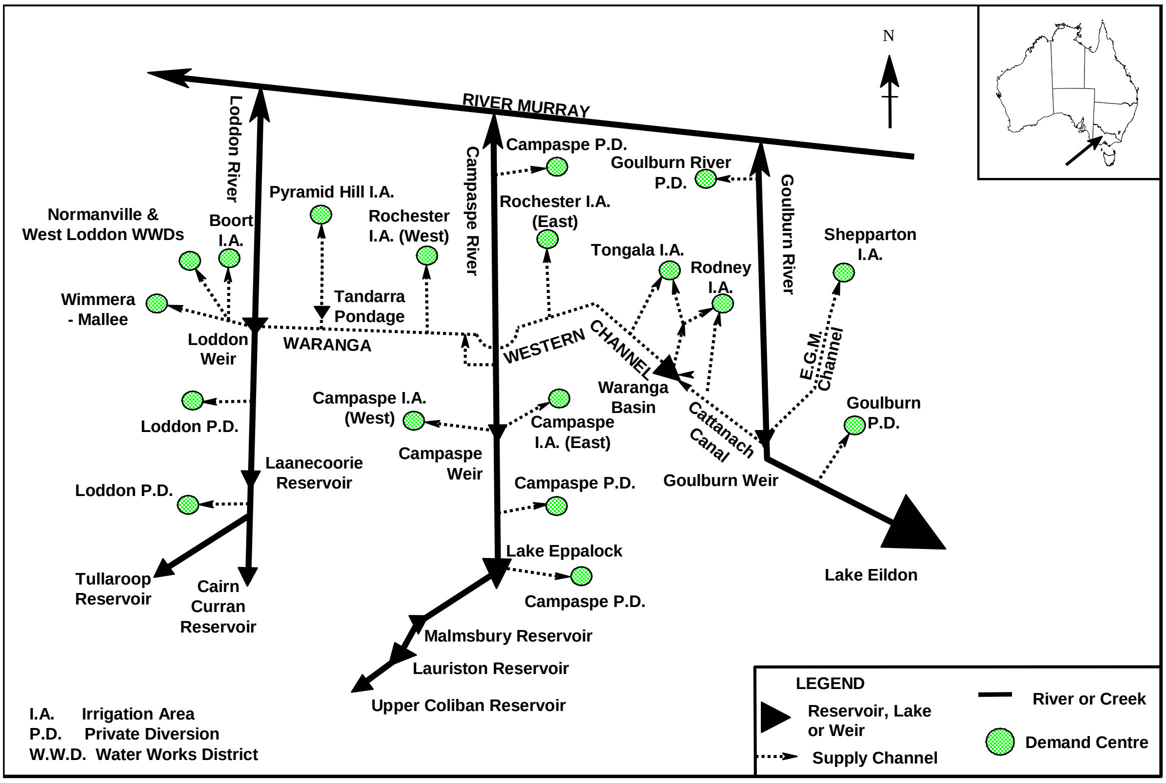

Figure 1. A simplified representation of the Goulburn Simulation Model

Irrigation is spread across dairy, mixed farming and a small but important horticultural industry. Water is made available to irrigators via the allocation process. An allocation gives the amount of water farmers have access to as a percentage of permanent entitlement. If a farmer holds an entitlement to 100 ML and allocations are 150%, they have access to 150 ML. Allocation updates are made through the irrigation year, and may only increase. Allocated entitlement can be traded temporarily (for use within the irrigation year).

In keeping with the need for security of supply, water allocation policy is conservative. Allocations are based primarily on the volume of water in storages. All water is allocated up to 100%. After that, no more is allocated until a conservative estimate of next year's demands can also be met. Any further water in storages is then made available to farmers.

Allocated entitlement (net of trading) is an upper limit. One reason farmers may not receive all the water they are entitled to is channel capacity constraints: the physical system has to be able to deliver the water. In some areas, in periods of high demand, rationing of water is necessary due to bottlenecks in the delivery system.

The system is managed by Goulburn-Murray Water, a corporatised government body. Goulburn-Murray Water has both irrigators, its customers, and the State government, its overseer, as stakeholders. Goulburn-Murray Water aims to maximize the water it provides to farmers, both in terms of allocations and deliveries: this also maximizes its sales revenues. At the same time, it must maintain security of supply, meet environmental flow targets, and keep within the Murray-Darling Basin Cap.

3. THE MODELLING FRAMEWORK

The aim of the modelling framework in this study is to provide a tool to help assess potential results of policy changes from an integrated economic-hydrologic system.

The hydrology is modelled using the Goulburn Simulation Model (GSM), built using the REALM software. The GSM simulates allocations and deliveries for given irrigation demands. It is a credible tool for policy analysis and planning in Victoria (Perera et al. 2003).

The GSM has been extended recently to allow simulation of the system with the inclusion of water trading (Weinmann et al. 2005).

The modelling described in this paper extends the work above in several ways:

- it allows for greater choice in managing irrigation water.
- the economic modelling is seasonal: farmers can reassess their plans at the start of each season of the irrigation year (spring, summer and autumn).
- it explicitly models uncertainty.

As noted above, farmer behaviour is an important part of simulating the system, and uncertainty is a key feature of farmer decisions. The emphasis in the economic modelling is on uncertainty, and how it influences irrigation water management.

Farmers are represented by three industries (dairy, horticulture, and mixed cropping and grazing) in ten of the major irrigation demand centres of the Goulburn system (a subset of the demand centres shown in Figure 1). There are 26 farmers in total (some areas have no horticulture).

Irrigation demands from the economic modelling are passed as inputs to the hydrologic model. The GSM attempts to deliver the water demanded, but it may not be able to do this, and actual deliveries, as well as any updates to allocations, are passed back as inputs to the economic model at the start of a new season (Figure 2).

At the start of each season, farmers reassess their plans in light of what has happened over the year to date and as more information about the remainder of the year comes in.

The year starts with an initial allocation. This is the only information farmers have when formulating an initial plan for the year. At the start of summer, an allocation update is announced. Farmers also know whether spring was wet or dry, and due to correlations between seasons, this provides some information on likely conditions over the remainder of the year. At the start of autumn, the only source of uncertainty remaining is how much water crops will need in autumn.

The economic modelling is short run in that permanent water entitlements and maximum crop areas are fixed (to mid-1990s levels, the most recent available data). Given these initial conditions, the model is run over 112 years of hydroclimatic data (inflows to storages, crop water demands, etc). The modelling gives an indication of how the current system would perform in a variety of hydroclimatic conditions. Future work may see a leap forward of 30-odd years to different sets of initial conditions.

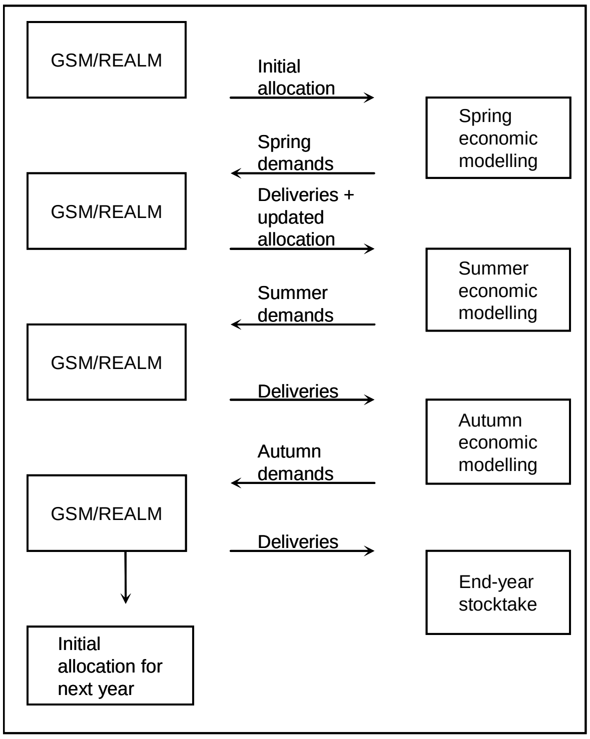

Figure 2. Schematic of the modelling framework

4. THE ECONOMIC MODELLING

At this stage, full integration has not been realized and the remainder of this paper discusses only the economic component. It is assumed that there are no constraints from the physical side of the system (access to water is not limited by the water delivery infrastructure). Allocations are taken from a previous run of the Goulburn Simulation Model, based on the models presented in Weinmann et al. (2005). While these allocations are not entirely consistent with the economic modelling below, they should show a similar pattern.

The core of the economic modelling is a constrained optimization problem for each ‘farmer’. Horticulture and mixed farmers maximize gross margins, while dairy farmers minimize costs of feeding their herd.

The equations below represent a simplified version of the spring model for horticulture.

$$Max\{returns\} = gm\frac{\delta^3}{w^3} + \sum_{m=1}^{3} ws^m twp^m \qquad (1)$$

subject to

$$\frac{\delta^1}{w^1} \leq a \quad (2)$$

$$\frac{\delta^m}{w^m} \leq \frac{\delta^{m-1}}{w^{m-1}} \Lambda \ m \geq 2 \quad (3)$$

$$\sum_{n=1}^{m} \delta^n + \sum_{n=1}^{m} ws^n \leq A^m W \Lambda \ m = 1,2,3 \quad (4)$$

where

m,n	all superscripts refer to the season
gm	gross margins ($/hectare)
δ	total irrigation water applied (ML)
w	irrigation water required (ML/hectare)
ws	water sales (negative for purchases) (ML)
twp	temporary water market price ($/ML)
a	maximum irrigable area (hectares)
A	allocation (%)
W	permanent water entitlement (ML)

Farmers choose irrigation quantities and water sales/purchases to maximize their returns (1), given that they cannot irrigate more than their maximum irrigable area (2), and must remain within their allocated entitlement (+ or - trade) (4). Once a decision not to irrigate an area is taken, crop yield from that area is lost for the year (3).

As discussed in Section 3, a and W are fixed based on current data. The uncertain parameters are w, twp and A. Thus there is uncertainty in the objective function and both the left-hand side and right-hand side of the constraints.

It is usual to also consider commodity prices (embedded in gm) as uncertain, and future work may see this included.

4.1. Discrete Stochastic Programming

Discrete stochastic programming was formulated by Cocks (1968). The technique is an extension of linear programming devised to deal with multistage problems 'where (any number of) the functional, restraint, and input-output coefficients are subject to discrete probability distributions'.

The discrete stochastic programming approach requires a discrete number of possible states of nature, and discrete probability distributions over these states of nature.

The technique is very flexible, but the dimensions of the problem increase exponentially with both the number of states of nature in any time period, and the number of time periods. For this reason, a parsimonious approach was taken:

- Three seasons rather than nine months were modelled. (Nine months would give a better match with the hydrological modelling, which is monthly. In addition, a monthly rather than a seasonal decision time-step may be more plausible)
- For each initial allocation, only two possible final allocation levels were considered, forgoing the possibility of an additional autumn increase, which occurs in practice about 20% of the time.
- Only 'wet' versus 'dry' rather than a more complicated representation of climate was considered.
- Commodity prices were not modelled as uncertain.

4.2. States of Nature

To implement a discrete stochastic program, uncertainty must be encapsulated in a small number of possible states. Each season was split into a 'wet' versus a 'dry' state, and allocations were split into a 'high' versus a 'low' level.

While the binary 'wet' versus 'dry' representation of climate may seem simplistic, two possible values over three seasons gives a total of eight possible patterns over the irrigation year.

The 112-year series of hydroclimatic data includes crop water requirements for each crop for each season. States for 'wet' and 'dry' were formed by dividing each series by the median to form wet and dry groups. An average was then taken over each group to stand for crop water requirements in a 'wet' season versus a 'dry' season. This method assumes that farmers aim to get it right on average: about 50% of the time they unintentionally end up with too much water, the other 50% of the time they unintentionally leave themselves short.

For horticulture, an assumption of having enough water on average may not be tenable. Rather, they may take the upper bound of each group as state values. If so, they would never lose revenue from not being able to irrigate fully, but they could almost always have made more by selling excess water (or buying less).

Expected final allocations can be either 'high' or 'low'. Initial allocations were split into bands of 20 percentage points, and a high versus a low value chosen for each band by finding natural breaks.

All up, there are two possible states for spring (wet and dry); eight for summer (wet spring-wet summer-high allocation to dry spring-dry summer-low allocation) and sixteen possible states of nature for autumn.

Values for expected temporary water market prices for each state of nature were taken from a full-information version of the same optimization models. That is, equilibrium prices for the system were calculated given the final allocation and crop water requirements. This is a sophisticated methodology, which implies access to and processing of a lot of information. Future work may consider rougher rules-of-thumb price expectations, or a focus on pessimistic cases.

4.3. Belief Formation

Having characterized the variability in terms of a discrete number of states of nature, the next question to consider is how farmers form beliefs over these events.

As a first-cut, beliefs were assumed to match historical relative frequency. This includes an analysis of correlations. For example, the strongest correlation was found to be between spring and summer seasonal conditions.

Future work may consider scenarios such as overweighting recent history or particularly worrisome states of nature.

4.4. Attitudes to Risk

Only risk neutrality is modelled in the current context: expected value maximization (expected cost minimization). Future work will consider how introducing risk aversion, most commonly represented through concavity in the objective function, influences decisions.

4.5. Water markets

For the purposes of this modelling it is assumed that all trade goes through a water exchange, similar to Watermove (the water exchange set up by Goulburn-Murray Water to facilitate trade). Farmers submit bids to buy or offers to sell water through the exchange, which include information on how much they would like to buy (sell), and the price they are willing to pay (accept). The water exchange finds the maximum amount of water that can be traded at a common pool price such that buyers pay at most what they bid and sellers receive at least what they offer. Not everyone will be successful, and priority is given to buyers with the highest bids (sellers with the lowest offers).

The discrete stochastic program provides the amount the farmer would like to buy or sell. This plan is based on an expected temporary water price (Section 4.2). While this expected price is a best guess, the actual price is only formed when the market itself is run. As it is difficult to predict exactly what the price will be, one end of the market is often long, and priority is given to buyers with the highest prices (sellers with the lowest prices), farmers wishing to buy water will bid the maximum amount they would be prepared to pay, and farmers wishing to sell water will bid the minimum they are willing to accept.

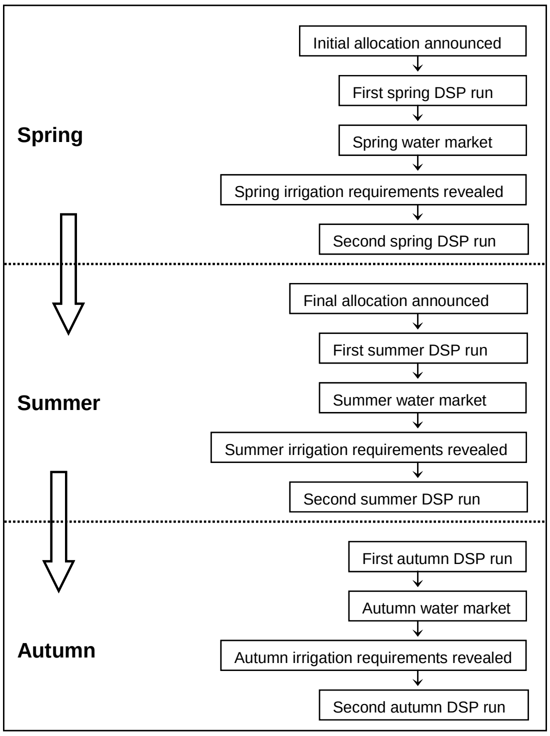

Figure 3. The economic modelling

4.6. A Second Discrete Stochastic Program

Before finalizing irrigation demands, farmers are given full knowledge of the current season's irrigation demands. This is more realistic than assuming they under or over-water because they can only make choices once every three months. With knowledge of the current season's crop water requirements and the results of the water market, farmers are given a chance to reformulate plans.

A summary of the process for the year is captured in Figure 3.

5. RESULTS

The economic modelling was run over 112 hydroclimate years. Recall that the only information farmers have at the start of the year is initial allocations. These are grouped into eight bands: this implies a maximum of eight initial plans per farmer. In fact, each 'farmer' has fewer than eight as some are the same for different initial allocation groups. Each horticulturalist only has one plan, which is to fully irrigate: expected water market prices are never high enough to tempt them to sell water instead.

Although farmers are given the freedom to choose a different strategy for each state of nature, plans are relatively simple: mostly, farmers plan to irrigate the same areas regardless of seasonal conditions; or they may, for example, have one plan if spring is wet and another if spring is dry.

The basic decision weighs up returns from irrigating versus water sales. Thus, it is uncertainty in water market prices and crop water requirements that lead to the ‘wrong’ choice being made. Mistakes are irreversible in the sense that crop areas not irrigated from the beginning are no longer available, and water, once used to irrigate, is sunk. Decisions about irrigation do not depend directly on allocations (only indirectly via the expected water price link).

Plans formed at the beginning of spring are usually followed. The most common reason for a change in plan is failing to buy water, which can force less area to be irrigated. The further along in the year, the more farmers have invested in a particular plan, and a dramatic change in circumstances is required to change the optimal plan.

An example is 2003: initial allocations are low, but farmers expect an increase in summer. Expected water prices are still low enough for dairy farmers to plan to irrigate pastures to provide the majority of energy needs, with grain providing a top-up. After final allocations are announced (the lowest on record at only 57%), expected prices jump markedly, and plans change to use more grain, up to the maximum allowed if autumn is dry. The cost of uncertainty is that more areas were irrigated during spring than required, to make these areas available later, and this water is now completely wasted. This case illustrates the importance of information and belief formation: while the (simulated) historical series for allocations may have suggested a sizable increase, model-based climate forecasts may not have been as optimistic.

On the other hand, uncertainty has little impact in high allocation years: there is a surplus of water in the system, water market prices are sure to stay low and each farmer plans to irrigate all areas.

6. CONCLUSIONS

This paper has outlined a framework set up to investigate how decisionmaking under uncertainty impacts on the outcomes of an integrated economic-hydrologic system. As the integration has not been completed yet, the paper has focused on the economic component, in particular, how irrigation water is managed under uncertainty.

Discrete stochastic programming was found to be appropriate for simulating responses to the types of uncertainty facing irrigators. The main limitation is the rapid growth in the dimensions of the model as the number of states of nature increases.

Despite the flexibility discrete stochastic programming allows, this application found only a small number of initial spring plans: these are relatively simple and tend to be followed through the year if possible.

These results are based on one set of assumptions about states of nature, belief formation and attitudes to risk. Future work will conduct sensitivity analyses on these assumptions.

Finally, these results are for mid-1990s conditions. To gauge how the system might perform in 20-30 years, the model will be run for different initial conditions, chosen to reflect the land use patterns and institutional environment for water resources likely to emerge in the Goulburn system.

7. ACKNOWLEDGMENTS

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