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Integrated hydrologic–economic modelling for analyzing water acquisition strategies in the Murray River Basin

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ABSTRACT

We describe a coupled hydrologic–economic spreadsheet model for the Murray-Darling Basin that allows analyses of water allocation and use by different sectors including agriculture and environment under alternative policy scenarios. The model is a simple, lumped optimisation model which includes partitioning of rainfall into runoff and evapotranspiration, a reach by reach water balance of the river system, irrigation demand and revenue generation. Groundwater is not considered because groundwater use is a small part of the overall water use. The model is used to optimize profit, diversions and flows subject to hydrological and economic constraints determined by the policy scenario.

We use the model to examine approaches of acquiring water for reallocation to the environment, and their impacts on irrigation water use and regional income from agriculture. We show that the optimal approach for acquisition depends on: economic factors, including the cost of water and the profits generated by its use; institutional factors, such as restrictions to trade between regions; and, hydrological factors, particularly the connectivity of and losses within the river network.

The volume of water to be acquired does not, in general, equal the volume to be allocated. For a downstream site, water must be acquired from upstream, and more water must be acquired than is to be allocated: the volume acquired is that to be allocated plus transmission losses between the locations of acquisition and allocation. For upstream sites, it is optimal to acquire some water from downstream, and less water must be acquired than is to be allocated: the volume acquired is that to be allocated, less the transmission losses no longer incurred between the locations of acquisition and allocation.

The volumes of water that must be acquired to satisfy an allocation target and maintain flows in the river system are affected by restrictions on trade between sub-catchments.

1. Introduction

Our study is motivated by the problem of acquiring, within a river system, fixed volumes of water for allocation to particular places of environmental concern. Within the Murray Basin in Australia, concerns about the over-allocation of water to irrigation and the consequent impact on the health of the river system, and particularly the impact on key environmental assets (MDBC, 2004), led state and federal governments to commit A$500 million over five years to the problem (COAG, 2004). The goal is to return to environmental use about 500 million m^3 annually (as a long term average) through various measures including the funding of water saving schemes and market-based acquisition. The water is to be

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used to restore key environmental assets. More recently, the federal government has launched an initiative to reduce over-allocations further, again including the funding of water saving schemes and market-based acquisition.

Standard linear and non-linear programming equilibrium methods for integrated hydrologic-economic models have been used in many river basins, including the Murray Basin, to examine general problems of acquisition and allocation of water (McKinney et al., 1999; Rosegrant et al., 2000; Rodgers et al., 2002; Quiggin, 1988, 1991). Qureshi et al. (2006, in press) use the approach to examine policy options for acquiring water for environmental allocation in the Murray Basin. They show that acquisition of environmental water pro-rata from all catchments is considerably more costly than taking water strictly from the least profitable industries. They also show that restricting water trades between different catchments further adds to the opportunity costs.

Qureshi et al. (2006, in press) estimate the opportunity cost of acquiring water under various policy options without reference to where the water is to be allocated and whether different amounts are required at different sites of environmental significance. Furthermore, their model does not account for transmission losses in the river system, and so it does not adjust the volume that must be acquired to make up for the losses.

Our purpose in this paper is to present a coupled hydrologic-economic model which is useful for assessing the various strategies for acquiring water for environmental allocation. Non-linearity in the hydrology leads us to adopt an iterative approach in which the hydrology and economic parts of the model are solved in turn, until the volume of water acquired across the system converges to a target volume for allocation at a particular site. The model is a regional optimisation model that does not consider individual farmer responses, which might differ from those implied in the optimised aggregate behaviour. We apply our model to the Murray Basin, and examine strategies for acquisition of water for environmental use.

2. The model

The model has three components: (1) hydrology, including the water balance in reservoirs, river reaches, and irrigation districts; (2) economics, including the calculation of benefits from water use by sector and demand site; and (3) institutional rules that impact the hydrologic and economic components. Water supply is determined through the water balance in the river system, while water demand is based on functional relationships between water and productive uses in irrigated agriculture. Water supply and demand are balanced such that economic benefits of water use are maximised subject to policy constraints.

The model is based on optimising the allocations of water to the various demand sites, and is therefore an equilibrium model. It uses annual volumes of rainfall, runoff, river flow and irrigation demand, aggregated at a sub-catchment scale. We consider that annual volumes are sufficient for our present purpose.

Our interest is in the imposition of new, fixed allocations to specific places in the river system. Such allocation changes the flows in the river, and hence the availability of water. Furthermore, transmission losses from upstream to downstream mean that the optimum distribution of acquisitions is affected by the flows and losses. Thus, the economic equilibrium solution to the new, fixed allocation affects flows and hence losses, and this in turn affects the equilibrium solution. Thus, in contrast to many other models (McKinney et al., 1999; Rosegrant et al., 2000; Rodgers et al., 2002; Quiggin, 1988, 1991; Qureshi et al., 2006, in press) that use a one-way flow of information from the hydrologic to economic components of an optimisation model, we use a fully coupled model that includes an iterative feedback loop (Fig. 1). We developed the model as an Excel spreadsheet, which is easy to implement and sufficient for the present purpose.

2.1. Hydrologic component

We model the river basin as a node-link network, in which nodes represent the boundaries of river reaches (Fig. 2). Inflows to these reaches are water flows from the headwaters of the river basin and runoff entering the reaches. Agricultural, municipal and industrial demand sites are spatially connected to the basin network.

We do not account for groundwater, which comprises about 5% of water use in the basin, or return flows from irrigation, for which we do not have reliable information.

The model is based on mass conservation:

$$\sum(\text{Water in}) - \sum(\text{Water out}) = 0 \quad (1)$$

Because the model is an equilibrium model, changes to storage are zero, and do not appear in Eq. (1). The equation applies to the whole river basin (where Water in is rain, and Water out is evapotranspiration, evaporation from open water and discharge from the mouth), and to any element within the basin, such as a dam or a river. In keeping with the first assumption, the only storage terms are major reservoirs.

In estimating runoff each of the sub-catchments is divided into three regions (upper, mid, lower) and several land uses including forests, grazing, dryland agriculture, irrigated agriculture, urban, and open water.

Rainfall, distributed spatially, is partitioned into evapotranspiration and runoff using the relationships developed by Raupach et al. (2001), and a method similar to that of Zhang et al. (1999).

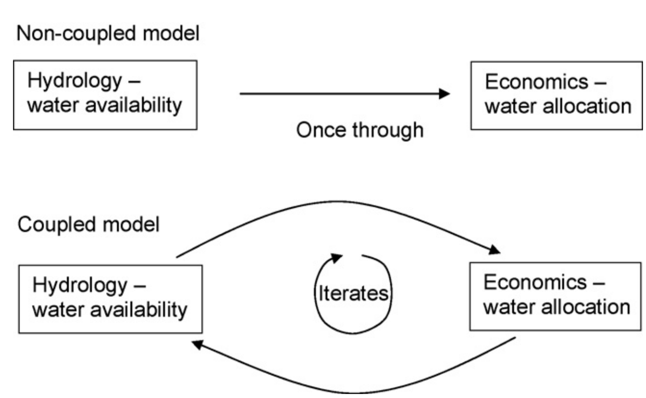

Fig. 1 – Schematic representation of coupled and non-coupled hydrology–economic models.