# conjunctive water management

## economic tools for evaluating alternative policy and management options

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ahmed hafi

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Australian Bureau of Agricultural and Resource Economics
GPO Box 1563 Canberra 2601

Telephone +61 2 6272 2000 Facsimile +61 2 6272 2001
Internet www.abareconomics.com

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# introduction

Total groundwater resources in the Murray Darling Basin are currently overallocated. In 2000-01, total allocations were estimated to be 3250 gigalitres a year, whereas sustainable groundwater yield was estimated to be only 2450 gigalitres a year (Earth Tech Engineering 2003). While aggregate groundwater extractions in the Murray Darling Basin were only half the sustainable yield in 2000-01 (Earth Tech Engineering 2003), extractions in conjunctive systems are expected to increase in the future through increasing consumptive and environmental demands and the cap on surface water diversions. Drier conditions have also resulted in increased investment in capacity to extract groundwater as farmers seek to maintain production through the more intensive use of partially utilised permits and the activation of latent permits.

The National Water Initiative (NWI) seeks to ensure that groundwater use is sustainable, and that the net economic benefits from water use are maximised. The potential to design more efficient and effective groundwater management policies will depend to some extent on the ability of decision makers to analyse the economic costs and benefits of alternative options. Predictive hydroeconomic models can be useful in these type of analyses.

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# the role of hydroeconomic models in evaluating alternative policy and management options

Hydroeconomic modeling combines an understanding of water resource systems with information on economic returns from alternative activities and institutional arrangements affecting water use decisions. Once these linkages have been defined, these models can be used to assess the economic and hydrological impacts of alternative water resource management policies. Some of the key issues that need to be considered when modeling water use in single and connected aquifers, and conjunctive use in groundwater and surface water systems, are detailed below.

## single aquifers

The derivation of an optimal pumping policy for a single aquifer requires that the economic value of the resource be maximised over a long period of time. This means that any carryover of groundwater stocks between years will need to be considered in the analysis. Other external costs tend to be ignored in these models, however, as it is assumed that the aquifer is not connected to other aquifers or an ecosystem. It is also assumed that groundwater entitlements can be traded within the aquifer. The optimal pumping policy prescribes a groundwater extraction level for any given level of groundwater stocks. This information is useful in determining adaptive groundwater extraction policies, and in understanding the implications of uncertainty surrounding key biophysical relationships.

## connected aquifers

The existence of interaquifer or aquifer stream connectivity requires that the economic impacts of connectivity be considered when setting sustainable yields for each component in the system. For each aquifer in the system, the groundwater extraction policy should take into account both current groundwater stocks and linkages between aquifers as actions taken by one may impose external benefits or costs on another. Once the optimal extraction rate is introduced, it may be possible to increase the net benefits from water use by allowing trade in groundwater entitlements between linked aquifers. Alternatively, it may be possible to introduce a system of user charges to optimise the distribution of groundwater resources between different users. Hydroeconomic models could be used to guide policy makers in setting and revising user charges to reflect these external costs and, hence, encouraging the more efficient use of groundwater.

## conjunctive use

A single resource use policy needs to be developed for areas where groundwater and surface water are used conjunctively. Guidelines for the allocation of groundwater for conjunctive licensees in some groundwater management areas (GMAs) are based solely on surface water allocations announced at the beginning of the irrigation season. In contrast, the optimal conjunctive use policy considers both the groundwater stock levels as well as surface water allocations announced at the beginning of the season.

An optimal conjunctive use policy prescribes, for each period, the optimal use of groundwater and surface water for any combination of the possible levels of surface water allocations and groundwater stocks. The policies for the use of the two resources are determined simultaneously in line with the significance of the interaction between surface water and groundwater in a conjunctive use setting.

# 3

# general features of hydroeconomic models

To be useful for policy analyses, a hydroeconomic model must contain information on three linked components:

- water use by farms in the catchment or the area overlying the aquifer
- groundwater and surface water flows and any interaction between these two systems and
- institutional arrangements for managing groundwater and surface water resources.

The level of detail in which each of these components is represented in the model can vary between hydroeconomic models. The level of detail in the representation of groundwater and surface water hydrology accounts for most of the differences between the various hydroeconomic models.

At a more general level, hydrogeological components in models can differ by the level of spatial aggregation (distributed parameter versus lumped parameter), the state of equilibriums in the groundwater flow process (steady or transient/dynamic) and the manner in which recharge and stream flows (stochastic or deterministic) are treated. In a distributed parameter specification, the groundwater and surface water processes are represented at a more disaggregated level than in a lumped parameter specification. A dynamic or transient specification adds a temporal dimension to the groundwater flow process by accounting for carry over effects, while stochastic recharge and stream flows enable explicit treatment of uncertainty.

The economic component of a hydroeconomic model is normally tailored to the specification of the groundwater and surface water flow processes in the model. A lumped parameter model may assume a single economic agent or a central planner, whereas a distributed parameter model may assume multiple agents. The behavioral assumptions for economic agents depend on the management regime assumed. If users have open access to the resource, competitive profit maximisation by individual agents is assumed and costs imposed by one user on another are not considered. If the system is managed optimally, all user costs will be considered, and the objective will be to maximise the economic value of the total resource. Under existing institutional arrangements, individual irrigators are assumed to maximise their profits. The impact of different forms of strategic behavior between multiple agents can be modeled with a distributed parameter model.

In the following sections, the main issues that need to be considered when developing hydroeconomic models are discussed. These issues include the level of spatial aggregation, the state of equilibriums and uncertainty surrounding recharge.

## *level of aggregation (distributed parameter versus lump parameter)*

The properties of aquifer material can change over space and, as the aquifer material influences the groundwater flow process through it, the groundwater flow process can also change over space. Similarly, the groundwater users on overlying land can be heterogeneous. For example, they can have different resource endowments, including land holdings and water licences and production activities. Given that each irrigator acts as a single economic agent, it is usually more appropriate to model a groundwater system as a number of separate users, each sharing a common pool of groundwater resources with different flow characteristics (distributed parameter model).

One of the key advantages of distributed parameter models is that they can be designed to incorporate behavior on individual farms and capture spatial as well as dynamic externalities of pumping through to its effect on the entire aquifer. Despite obvious benefits, a distributed parameter approach requires substantial resources in collecting data on hydrogeological and economic parameters from a large number of locations. Distributed parameter models can easily become very large and intractable.

The MODFLOW model developed by the US Geological Survey is a distributed parameter model that represents groundwater movements through space and time. It is now a standard modeling tool for hydrologists. It would be useful if it could be transformed into a hydroeconomic model by incorporating an economic component. However, because of the use of a large number of small cells and finite difference mathematical specification, it is difficult to transform. An alternative is to use response matrices obtained from MODFLOW to represent the hydrological component of a hydroeconomic model as demonstrated by Bredehoeft and Young (1970) and Young, Daubert and Morel-Seytoux (1985). If the study area can be represented in a small number of cells, then the set of finite difference equations defining the groundwater flow process can be directly embedded in a hydroeconomic model, as illustrated by McKinney and Savitsky (2003).

Sometimes, information required by policy makers and water managers may be developed from simpler models where water users and the underlying aquifer cells are grouped into a few regions. Such models are called lumped parameter models. The advantages of lumped parameter models are that they are easy to build, maintain and work with and require less data. Most of the empirical studies on the economics of groundwater use have lumped parameter representation of the groundwater process. This approach was employed by Burt (1964a,b), Buras (1963), Provencher and Burt (1994), Knap and Olson (1995), Hafi and Cao (2002) and Hafi (2003).

## *state of equilibrium of the system – steady or transient (dynamic)*

Just like the distinction between a distributed parameter and a lumped parameter model, exploring the merits of steady state against transient state models may also help better address the question of what type of model is best suited to provide the policy information required. If there is a tendency for a natural resource system to approach a steady state after a shock and remain in that state until the next shock, then the analyst could collapse the dynamic system to a steady state system. Even though a given steady state is a static state, the comparative statics of the system can be easily explored to obtain key policy information. A system that has reached a steady state can be represented in a much smaller set of equations than a transient system. This feature makes it analytically more tractable, with some of these models easily solved in a spreadsheet environment.

Knowledge of the steady state solution has significant value and, for a single or a two-linked aquifer system, the steady state levels of hydraulic head, volume of water pumped per year and the marginal value of groundwater can be derived analytically. For a data intensive distributed parameter specification, it is advisable to use a steady state model first until reliable data on aquifer storage properties are collected so that it can be expanded to a transient model.

If the key information required includes carryover impacts of current pumping actions and recharge events, then a transient or dynamic model adds the necessary temporal dimension to the spatial dimensions in a steady state distributed parameter model.

## *stochastic or certainty equivalent*

The natural recharge that largely replenishes groundwater stocks is stochastic as it depends on weather. The weather also influences groundwater pumping as it determines rainfall, surface water supplies and crop evaporative demand and thus the pumping required in meeting any deficit in crop evaporative demand. The stochastic nature of both recharge (supply) and demand for groundwater in the current time period results in uncertainties of future groundwater stocks. The modeling task now becomes more complicated, as the best allocation rules for surface water and groundwater resources need to be found when surfaced water allocations, groundwater recharge, rainfall and crop evaporative demands are unknown.

There are a number of methods (with differing degrees of complexity) that can be used to address this problem. One method is to use stochastic dynamic programming and take a planning approach where the planning is carried out sequentially: first at a short run; second at an intermediate run, by incorporating (assembling) short run solutions; and third at a long run by incorporating intermediate run solutions, thereby making use of all the information known at each decision point. The short run may consider an irrigation year, while the long run considers a period of a number of irrigation years long enough for the system to reach equilibrium. Short run decision making involves allocation of the available land area and surface water and groundwater between a number of cropping/pasture enterprises for each year. Long run decision making involves allocation of groundwater stocks and seasonal recharges over a long planning horizon. For each year, the model takes into account the economic value of the remaining groundwater stocks carried over to next year and decisions are made by equating the expected net benefit from allocating resources for the current period and the expected net benefit from saving the resources for the future.

The difficulty with the stochastic dynamic programming approach is that when the number of state variables increases the model becomes both analytically and numerically intractable, and for that reason it works better with a lumped parameter approach as the number of state variables can be collapsed. This is evident in most applications of stochastic dynamic programming to the economics of groundwater use. Burt (1964a,b), Buras (1963), Provencher and Burt (1994), Knap and Olson (1995), Hafi and Cao (2002) and Hafi (2003) all use a lumped parameter approach.

Linked simulation optimisation is another way to handle stochastic recharge and seasonal conditions. In this approach, a large number of realisations of future recharge and seasonal conditions are drawn from a known distribution of historical events. The model is run for each realisation of future recharge and seasonal conditions and the distributions of key impact variables are used to derive policy and management implications. In most distributed parameter models, stochastic recharge and other weather variables are handled in this manner – for example, Bredehoeft and Young (1970) and Young, Duabert and Morel-Seytoux (1985).

In the case of steady state models, the long term expected (or certainty equivalent values) recharge, rainfall, crop evaporative demand and surface water availability are used, as the objective is to solve for the long term expected pumping rate and groundwater stock level. To be realistic, as recharge is stochastic, steady state equilibrium is better seen as a target, but one that is rarely achieved in reality (Burt 1967). The use of certainty equivalent recharges with steady state models in deriving optimal pumping policy works better when the groundwater stocks are in the neighborhood of the stochastic or steady state equilibrium.

There are a number of linked simulation optimisation approaches that lie between the approaches of using all possible realisations of future recharge patterns and the use of certainty equivalent recharge.

# 4

# key components of hydroeconomic models

## economic component

The economic component of a hydroeconomic model estimates the benefits and costs of groundwater use. These benefits and costs can be estimated for planning horizons of different lengths (annual, over a number of years or for an infinite planning horizon). The benefits and costs realised in a short planning horizon, such as a season or a year, form the building blocks needed for estimating benefits and costs over a longer planning horizon.

In a conjunctive surface water/groundwater system, both surface water and groundwater are used as inputs to agricultural production. The value of an additional unit of water used for consumptive purposes (value of marginal product) declines as the volume of water used increases. The relationship between the value of marginal product and the volume of water used (the demand curve for water) forms the basis for estimating the benefits of water use. The benefits of using water to irrigate crops and pastures are encapsulated in this value of marginal product or demand curve for water. The costs of groundwater use include pumping costs, which tend to increase as groundwater pumping increases because of the additional pump lift required when the water table falls. Hydroeconomic models are specified to capture the impact of falling water tables on pumping costs. The short run cost of groundwater pumping is the product of the volume of water pumped, and the unit cost of pumping.

In a competitive or an open access environment, the profit maximising level of groundwater use for each groundwater user in each year will occur at the point where the cost of pumping an additional unit of water (that is, marginal cost) equals the value of marginal product. In such an environment, however, there may be additional costs in excess of the marginal cost of extracting water. Where these additional 'user' costs exist, the efficient level of extraction for each user will occur at the point where the marginal cost of extracting water plus user costs are equated to the value of the marginal product derived from using water.

The behavioral assumptions in the economic component of a model depend on the management regime that needs to be simulated. If users have open access to the resource, competitive profit maximisation is assumed. If the system is optimally managed the criterion of maximising economic value of the shared resource is used. Competitive profit maximisation is also assumed as the behavioral assumption along with the incorporation in the model of the institutional arrangements to achieve sustainable use of the resource. If there are no institutional arrangements to restrict resource access, the presence of user costs may provide adequate incentives for multiple agents to behave strategically in extracting groundwater. Models can also be designed to simulate various forms of strategic behavior between multiple agents extracting groundwater from a shared resource.

## *hydrogeological component*

The evolution of the state of the groundwater and surface water system is represented by a dynamic state equation for hydraulic head that is indicative of groundwater stocks and the volume of surface water available for use in each year. Pumping groundwater and recharge from natural sources and irrigation in a given year will result in a series of delayed responses in hydraulic head in the aquifer. The state equations for groundwater stocks incorporate the relationship between the hydraulic head, pumping actions and recharge events. The parameters of these response relationships depend on the hydraulic properties of the aquifer material. If aquifer–stream interactions are significant, the state equations for hydraulic head also incorporate the impact on hydraulic head of leakage to and from the stream. Stream leakage to or from the aquifer can be defined as a function of the difference between the stream water level (stage), and the hydraulic head beneath the stream bed.

## 5

# common types of hydroeconomic models

The relative importance of spatial disaggregation, the state of equilibriums and uncertain recharge that need to be accounted for in the modeling process will often differ between regions. This will also be the case for the information needs of water resource managers. Different modeling situations encountered by researchers in the past have resulted in a wide range of models that are documented in the literature. A review of documented hydroeconomic models suggests that they can be classified in the following manner:

- **steady state lumped parameter models**
    - single aquifer
    - multiple aquifer
- **dynamic lumped parameter models**
    - single aquifer
    - multiple aquifer
    - conjunctive use of surface water and groundwater
- **distributed parameter models**

Different types of hydroeconomic models are outlined in the following sections. For each type of model a brief description on the hydrological and economic components is given followed by a discussion of its usefulness in deriving policy relevant information.

## *steady state lumped parameter models*

If the hydrological component of a groundwater system has reached a steady state, it means that the variable chosen to represent the state of the system, such as hydraulic head, remains unchanged. A system that has reached a steady state can be represented in a much smaller set of equations than a transient system. For an aquifer manager whose objective is to maximise the economic value of the resource, a steady state in groundwater stocks (state variable) is always accompanied by a steady state in the marginal value of an additional unit of groundwater stocks (co-state variable).

In the derivation of a set of equations for a steady state system, it is assumed that the levels of each state and co-state variable do not change significantly between successive years when close to the steady state. This property enables the time dimension of the system to be ignored and the set of simultaneous equations representing the steady state to be solved analytically. Even if the system should more appropriately be modeled as a transient system, the knowledge of the steady state levels of hydraulic head, volume of water pumped per year, and the marginal value of groundwater stocks has significant value.

## single aquifer

In the case of a single aquifer, the certainty equivalent pumping policy can be derived analytically. The steady state groundwater stock is a function of demand, change in unit pumping costs per metre change in hydraulic head, the storage coefficient and a discount rate. The derivation of the steady state solution for a single aquifer involves three sequential steps (Conrad and Clark 1987):

> **step 1: estimate optimal groundwater pumping** – in the absence of return flows and when there is no interaction with adjacent aquifers, the annual optimal groundwater pumping level in the certainty equivalent steady state is equal to the expected value of annual recharge.

> **step 2: estimate marginal value of groundwater stocks** – use the optimal groundwater extraction level derived in step 1 along with the discount rate, the rate of change in unit pumping costs per metre change in hydraulic head and the storage coefficient of the aquifer to estimate the marginal value of groundwater stocks.

> **step 3: estimate hydraulic head** – use the marginal value of groundwater stocks estimated in step 2 along with water demand parameters to estimate the steady state hydraulic head or the stock level.

## two-linked aquifers

The data requirement for each of the linked aquifers is similar to that for a single aquifer, but additional data are also required on the leakage coefficient in order to represent the leakage between the two aquifers. For each aquifer, the actual impact of leakage to or from the other aquifer depends on the hydraulic heads of both aquifers. Therefore, the leakage coefficient provides the link between the two aquifers. The set of equations representing the steady state of a two-linked aquifer system is twice as large as that of a single aquifer system, and is more complicated owing to the leakage relationship. Despite this, these equations can be solved sequentially in a spreadsheet. Hafi and Cao (2002) have used steady state levels of state and control variables derived in this manner as the initial values in their stochastic dynamic programming model of two linked aquifers.

These equations can be used to estimate, for each aquifer, the steady state level of hydraulic head, volumes of water pumped per year, and the marginal value of groundwater stocks.

### *policy relevance of steady state solution*

Knowledge of the steady state solution can guide groundwater managers in decisions on groundwater allocations. If the aquifer hydraulic head in a year is lower than the steady state level, the optimal groundwater allocation in that year is also lower than the steady state allocation, and vice versa. If the hydraulic head is lower than the steady state level, a cut in pumping levels as prescribed by the steady state pumping policy will contribute to the rebuilding of groundwater stocks over time. If the initial hydraulic heads of the aquifers are higher than the corresponding steady state levels, the optimal pumping policy prescribes higher pumping levels compared with that of the steady state in the initial years so that both the hydraulic head and pumping levels approach the steady state levels.

However, to be able to review groundwater allocation decisions more regularly, the optimal groundwater extraction level for the hydraulic head must be known for each year – or more generally, the optimal pumping policy that defines the pumping level for any hydraulic head must be known. The derivation of the optimal pumping policy requires consideration of any carryover of groundwater stocks, and will be discussed under dynamic lumped parameter models.

## *dynamic lumped parameter models*

The use of certainty equivalent recharge with steady state models for deriving optimal pumping policy works better when the groundwater stocks are in the neighborhood of the steady state equilibrium. Stochastic rainfall, surface water supplies and crop evaporative demand mean excess demand for groundwater for irrigation is also stochastic. The combination of stochastic demand and groundwater recharge results in stochastic hydraulic head, and consequently, as Burt (1967) pointed out, a certainty equivalent steady state may not be achieved in reality. As the level of each state and co-state variable is expected to change over time, groundwater systems should be more appropriately modeled as dynamic or transient systems. Given the capacity of aquifers to store large volumes of water, a dynamic system will enable us to consider carrying over water to increase the overall economic value of the groundwater stocks.

## single aquifer model

A dynamic single aquifer model considers groundwater management with stochastic recharge. The hydrological component consists of one state transition equation for hydraulic head, while the economic component is represented by a benefit function for the use of groundwater for irrigation and a cost function where the unit cost of groundwater pumping is a function of hydraulic head. The decision variable is the volume of groundwater pumped. The storage coefficient translates the impact of groundwater pumping and stochastic recharge on the hydraulic head. Pumping costs increase as hydraulic head decreases. Data requirements include parameters for the value of marginal product function for water, storage coefficient, initial hydraulic head, maximum hydraulic head, and the distribution of stochastic recharge.

Given a very long planning horizon, the problem for the groundwater resource manager is to find groundwater extraction levels for each year that maximise the expected present value of groundwater stocks over the planning horizon. The model will solve for the optimal pumping policy, which is a function of hydraulic head, $x = f(h)$, and the steady state levels of the state and decision variables.

### *policy and management relevance*

The optimal pumping policy derived would show that the optimal pumping level increases with the hydraulic head (that is, the groundwater stock level) of the aquifer. Knowledge of the optimal pumping policy along with the steady state levels of the state and decision variables may help the aquifer manager in setting the optimal groundwater allocation for a given hydraulic head. For example:

> In general, if the hydraulic head of the aquifer in a given year is lower than the steady state level, the optimal groundwater allocation in that year is also lower than the steady state allocation, and vice versa.

> Assume that, in year *t*, the aquifer manager determines the hydraulic head to be $h_t$ , then an optimal pumping level of $x_t = f(h_t)$ is selected from the optimal pumping policy. In the same year, the aquifer manager observes a particular recharge, $\varepsilon_t$ , that will be credited for the next year. For the next year, the aquifer manager derives the hydraulic head by using the relationship $h_{t+1} = h_t - f(h_t) + \varepsilon_t$ and the optimal pumping level using $x_{t+1} = f(h_{t+1})$ , and so on. The process by which the optimal pumping policy is expected to lead to a steady state regardless of the initial state is explained below.

> If the initial hydraulic head is lower than the steady state level, the optimal pumping policy when applied sequentially over a sufficiently long time is

expected to lead to steady state pumping and hydraulic head levels. In this case, reduced pumping levels compared with the steady state level in the early years contribute to the rebuilding of groundwater stocks.

- > If the initial hydraulic head is higher than the steady state level, the optimal pumping policy will result in higher pumping levels compared with steady state levels in the initial years, which will lead to a decline in groundwater stocks. The optimal pumping policy will ultimately lead to steady state pumping and hydraulic head levels.

The time paths for the hydraulic head and pumping levels when the optimal pumping policy is applied over a large number of years for a given initial hydraulic head can be simulated. The time paths represent the optimal approach to the optimal steady state. Optimal time paths are derived in modeling studies reported in Hafi and Cao (2002) and Hafi (2003).

## two-linked aquifers

Now consider two aquifers. These aquifers could be horizontally linked, each with an overlying land area that is irrigated with water pumped from the aquifer. Alternatively, they could be vertically linked with the same overlying land area, with some farmers pumping water from the shallow aquifer and other farmers pumping from the deep aquifer. The model can also be adapted to a case where an aquifer discharges to a river or vice versa.

For each aquifer, it is assumed that the state transition equation for the hydraulic head is specified, that the benefit function for groundwater use for irrigation and the unit cost functions for groundwater pumping are specified, and the parameters for the distribution of stochastic recharge are known. The leakage coefficient that is common to both aquifers captures the effect on the hydraulic head of water conductivity between the two aquifers. Dixon (1991) and Hafi and Cao (2002) have employed a simple parameterisation of the leakage coefficient. In their studies, for each aquifer, the effect on the hydraulic head of water conductivity between the two aquifers is defined as some fraction, $\alpha$ (leakage coefficient) of the difference between its hydraulic head and that of the adjacent aquifer (hydraulic gradient). When $\alpha = 0$, the two adjacent aquifers are hydrologically separate and when $\alpha = 0.5$, the aquifers are fully connected. The value of $\alpha$ also has implications for defining property rights. For example, if $\alpha = 0$, this means no leakage, and that an exclusive property rights can be defined for each of the adjacent aquifers.

The problem for the groundwater manager in a two aquifer system is to find an optimal extraction policy which prescribes for each aquifer and any given combination of groundwater stocks in both aquifers, the optimal pumping volume that maximises the economic value of the groundwater stocks in the linked system. If the objective of maximising the economic value of the linked resources is chosen, the model internalises the intertemporal and spatial effects of groundwater pumping. The intertemporal effects of groundwater use arise as current pumping decisions affect the state at the end of the period, and thus future net benefits. The spatial effects arise as decisions by farms irrigated from one aquifer affect the farms irrigated from the adjacent aquifer because of leakage externalities.

### *policy and management relevance*

Current groundwater allocations for a groundwater system are based on the estimated long term average recharge adjusted for any discharge requirement for dependent ecosystems. There is little evidence that these allocations are based on extraction policies that have the characteristics of a socially optimal extraction policy. A socially optimal extraction policy can be implemented by using optimal quotas or pumping taxes.

For each aquifer and combination of groundwater stocks in both aquifers, the optimal quota is set at the optimal extraction level. Irrigators in each aquifer can then be allocated tradable shares of this optimal quota. Once the optimal extraction quotas are set and tradable shares are allocated, trading of groundwater between the linked aquifers can be allowed under trading rules based on the interaction between the two aquifers. Before implementing this type of scheme it is important to ensure that the benefits of trade outweigh the expected costs of administering and monitoring the trading system. Administration of optimal quotas has some difficulties as the optimal quotas vary over time and the aquifer hydraulic heads need to be continuously monitored.

For each aquifer and any given combination of groundwater stocks in both aquifers, optimal pumping taxes can be derived by comparing the model solution obtained with the objective of maximising the economic value of the linked resources with the solution obtained assuming competitive open access. Under open access, each aquifer manager does not consider the effect of pumping in the current year on the hydraulic head of the aquifers in the subsequent years, and consequently puts a zero value on the groundwater stocks of the two aquifers. Contrary to this, in the solution obtained for a socially optimal extraction regime, for each aquifer the impact of pumping on the value of groundwater stocks will be internalised.

For each aquifer and any given combination of groundwater stocks in both aquifers, an optimal pumping tax can be set at the estimated value of the impact of pumping on the value of groundwater stocks. Replacing existing allocations with optimal taxes can be expected to help achieve the socially optimal extraction policy. However, administration of such a policy is fraught, as the optimal tax rates need to be calculated each year as they vary over time and the aquifer hydraulic head needs to be continuously monitored. Alternatively, for each aquifer, steady state taxes may be imposed even though this may delay approaching the steady state.

## conjunctive use of surface water and groundwater

One of the key economic issues faced by managers of a conjunctive water use system is the optimal joint use of surface water and groundwater stocks. Where there is significant interaction between surface water and groundwater, policies on surface water and groundwater should be determined simultaneously. The model formulated needs to incorporate the dynamics of the surface water and groundwater system for the case study area: with water demand; groundwater extraction costs; stochastic recharge; and surface water availability. Examples of modeling conjunctive use of groundwater and surface water can be found in Burt (1964a,b), Buras (1963), Provencher and Burt (1994), Knap and Olson (1995) and Hafi (2003).

A model for the conjunctive use of groundwater and surface water can take a number of different forms depending on the number of state and control variables included. In its basic form, a model may be designed to derive the optimal allocation rules for the use of surface water and groundwater in agricultural production when announced allocations for surface water, recharge to groundwater aquifers, rainfall and crop evaporative demands are unknown. The key features of the model include the allocation of surface water available for the whole irrigation season between intraseasonal periods (spring, summer and autumn) and the allocation of groundwater stocks and seasonal recharge over a planning horizon of a number of years.

### *hydrological component*

The time step used in a conjunctive use model should more appropriately be an intraseasonal period. In most irrigation regions in the Murray Darling Basin, there are three key intraseasonal periods (spring, summer and autumn) in each irrigation season, which commences in August and ends in May. If there are $t = 1,2,...,T$ intraseasonal periods in the planning horizon, the length of the planning horizon in years is given by $T/3$. The surface water and groundwater system in the study area can be modeled to have two state variables; surface water allocation ($s_t$) and groundwater stocks ($h_t$) and two control variables; volume of groundwater pumped from the aquifer ($x^g_t$) and volume of surface water used ($x^s_t$) in intraseasonal period *t*. The model can also have another state variable for the intraseasonal period, to indicate the position of a given *t* in the cycle (spring, summer or autumn), which repeats itself in each irrigation season. For simplicity, the winter intraseasonal period may be overlooked, as little is planted and little irrigation water is used in this period. In total, the model could have three state variables and two control variables. Dudley, Rekils and Burt (1975) have used this approach to handle the intraseasonal allocation of water and land when surface water availability and seasonal conditions are unknown.

Given stochastic stream flows and groundwater recharge, state variables for surface water and groundwater are both stochastic. The parameters of the distribution of stochastic stream flows and groundwater recharge are assumed to be known.

### *economic component*

In a conjunctive surface water and groundwater system, water from surface sources such as rainfall and river flows are conjunctively used with groundwater in agricultural production. In the model, benefit functions for the conjunctive use of surface water and groundwater and the unit cost function for groundwater pumped and surface water delivered are specified separately for each intraseasonal period. The optimisation problem faced by a water manager in an intraseasonal period is to select ($x^s_t$) and ($x^g_t$) to maximise the net benefits of water use, subject to groundwater stocks and surface water availability at the beginning of the period.

The model solution for the efficient joint use of groundwater and surface water resources over the long run is derived by maximising the economic value of water drawn from the aquifer and surface water resources used for irrigation. In such a solution it is assumed that farmers include the impacts of current groundwater withdrawal on future groundwater levels in their decisions. In each intraseasonal period, the model takes into account the economic value of remaining surface water allocations and groundwater stocks carried over to the next period. In this manner, at each intraseasonal period, decisions are made by equating the expected marginal net benefit from allocating resources over the remainder of the current period and the discounted expected marginal net benefit from saving the resources for the following period.

The model is then applied to obtain a socially optimal groundwater and surface water use policy. First, for each intraseasonal period, optimal volumes of groundwater pumped and surface water diverted (control variable levels) are computed for the two-dimensional space of hydraulic head (groundwater stocks) and surface water volumes available at the beginning of the intraseasonal period (state variables). Second, the expected time paths for each of the control and state variables are computed if the socially optimal water use policy were to be followed.

### *policy and management relevance*

The optimal conjunctive use policy prescribes, for each intraseasonal period, the optimal use of groundwater and surface water for any combination of the possible levels of surface water allocations and groundwater stocks. The policies for the use of the two resources are thus determined simultaneously given the significance of the interaction between surface water and groundwater in a conjunctive use setting.

For each intraseasonal period and for any given levels of hydraulic head and surface water allocation, water authorities could determine the joint groundwater and surface water allocations at levels prescribed by the optimal conjunctive use policy. Currently, the allocation of groundwater for conjunctive licensees in some groundwater management areas is based solely on the surface water allocation announced at the beginning of the irrigation season. The optimal conjunctive use policy derived from the model, however, considers groundwater stock levels as well as surface water allocations announced at the beginning of the season. In addition, by incorporating intraseasonal periods in the model, the conjunctive use policy goes one step further by prescribing how a given volume of surface water should be allocated between intraseasonal periods. This is important because in conjunctive water management groundwater performs a stabilising role by helping cover any intraseasonal deficits in surface water availabilities.

The optimal conjunctive use policy when applied sequentially over time is expected to lead to both the pumping and hydraulic head levels (groundwater stocks) approaching steady state levels. This is true for any combination of initial states of the resources.

The conjunctive use policy may be applied as a tool for adaptive management of water resources.

## *distributed parameter models*

In many countries the MODFLOW model developed by the US Geological Survey is used to characterise groundwater movement through space and time (McDonald and Harbaugh 1988). It is now a standard modeling tool for hydrologists and the number of groundwater systems modeled in Australia using this framework is expected to grow in the future. However, it is difficult to transform MODFLOW into a tractable hydroeconomic model by adding an economic component to its finite difference mathematical specification. The most common alternative is to use response matrices obtained with MODFLOW to represent the hydrological component of a hydroeconomic model. If the groundwater system can be characterised by a small number of cells, the set of finite difference groundwater equations can be directly embedded as a constraint in a hydroeconomic model.

Whichever method is used, a distributed parameter hydroeconomic model has three linked components: the use of water by farms in the catchment; the groundwater and surface water flow processes and their interaction; and a water authority that manages groundwater and surface water resources. The representation of groundwater and surface water hydrology in this model is more comprehensive than in lumped parameter hydroeconomic models. A distributed parameter hydroeconomic model combines detailed hydrological specification with relevant economic relationships between water prices at different sites to mirror the dynamic groundwater and surface water flow processes (Bredehoeft and Young 1970; Young, Daubert and Morel-Seytoux 1986).

### key features

The distributed parameter approach differs from many documented empirical approaches to economic modeling of groundwater extraction in that water movement over both space and time is represented. This improvement enables researchers to conduct research on a range of groundwater systems with multiple agents and components. Ecosystems, such as streams, rivers and wetlands, that depend on the aquifer system can also be incorporated. The key features of distributed parameter models are listed below.

- A hydrological basin is modeled as a set of small cells rather than a single large cell, to account for lateral and vertical variation in hydrogeological properties and the delayed response of hydraulic head to pumping and recharge. The incorporation of a delayed response is a significant improvement. For example, for the same eventual response, the longer the aquifer cell takes to respond, the smaller will be the present value of future costs.

- The behavior on individual farms is incorporated and the dynamic externalities of pumping resulting from its effect on the aquifer are captured.
- Pumping cost is related to the hydraulic head at the pumping site rather than the average hydraulic head for the aquifer. In a water basin, pumping may be concentrated over space and time – in which case, relating pumping costs to average hydraulic head may be misleading. This is because aquifer characteristics and drawdown can vary over space.
- Hydraulic management goals are incorporated to ensure that the costs of waterlogging, sea water intrusion, aquifer subsidence and reduced base flows are minimised.
- Different assumptions on the strategic behavior of farmers (in the absence of policy intervention) can be made when running the model. Three such behaviors are listed below.
  - Farmers act myopically and ignore the impact of their current actions on future groundwater levels, surface water availabilities downstream and other externalities.
  - Farmers act with some foresight and consider the impact of their current actions on future groundwater levels in their wells only.
  - Farmers collude to achieve the socially optimal outcome by including in their decisions the impacts of their current actions on future groundwater levels in all wells and surface water availability downstream.
- Policy options aimed at achieving socially optimal use can be evaluated. For example, these options could include the allocation of groundwater and surface water with or without trade, water use taxes or subsidies etc.

## hydrological component

The hydrological component includes state equations and constraints based on hydraulic management considerations. The evolution of the state of the system is represented by dynamic state equations for hydraulic head at each cell. For each cell, pumping groundwater and recharge from irrigation in a given year would result in a series of delayed responses in hydraulic heads in all cells. The state equation, for each cell, incorporates all the relationships between its hydraulic head and pumping actions and recharge events at all cells. The parameters of each of these response relationships depend on the hydraulic properties of the aquifer material separating the cells and the distance between the cells. In general, the strength of the response in a selected cell diminishes as the distance between it and the cell from which water is pumped/recharged increases. The delayed response functions for hydraulic head in all aquifer cells from the return flows from irrigation from a cell are the same as for groundwater pumping.

If the response matrix approach is to be taken, these matrices can be estimated by running MODFLOW in transient mode by introducing, for each cell, a small pumping shock in the first year and measuring the responses in all cells in all future years.

If aquifer–stream interactions are significant, the state equations for stream flow at different stream segments and river flow in different subcatchments can also be included.

Hydraulic management considerations give rise to bounds on the hydraulic head of the aquifer at some observation cells. These constraints ensure that there is no water logging, seawater intrusion, aquifer subsidence or significant reduction in base flows, or that the probability of any of these events occurring does not exceed a threshold.

The state equations for stream flow incorporate net leakage to or from the aquifer. Stream water leakage to an aquifer can occur if the hydraulic head beneath the stream bed falls below the stream stage through excessive groundwater pumping by upstream farms. Conversely, groundwater leakage from an aquifer to a stream can occur when the hydraulic head beneath a stream bed rises above the stream stage through high recharge volumes from upstream areas. Stream leakage to or from the aquifer can be defined as a function of the difference between the stream water level (stage), and the hydraulic head beneath the stream bed.

## economic component

The specification of the economic component depends on the farmer behavior assumed.

> **behavior 1:** *Farmers act myopically and ignore the impact of their current actions on future groundwater levels and surface water availabilities downstream and other externalities.*

In this case the objective is for each farm to maximise short run profit from the use of water resources in agriculture. The unit cost of groundwater pumping is a linear function of the drawdown at the pumping site. For each farm, optimal water use is derived by equating the marginal value product of water to pumping costs in the case of groundwater and delivery charges in the case of surface water.

> **behavior 2:** *Farmers act with some foresight and consider the impact of their current actions on future groundwater levels in their wells only.*

In this case the objective is for each farm to maximise the net present value from the use of water resources in agriculture over an infinite or a sufficiently long finite time horizon. The unit cost of groundwater pumping is a linear function of the drawdown at the pumping site. For each farm, optimal groundwater extractions are derived by equating the marginal value product of water to pumping cost plus the private costs of the groundwater stocks less private return flow credits over the remainder of the planning horizon. For each farm, optimal surface water use is derived by equating the marginal value product of water to the delivery charge less private return flow credits. Social costs/benefits of current groundwater withdrawals/return flows over the remainder of the planning horizon are ignored.

> **behavior 3:** *Farmers collude to achieve the socially optimal outcome by including in their decisions, the impacts of their current actions on future groundwater levels in all wells and surface water availability downstream.*

In this case the objective is for the whole catchment to maximise the net present value from the use of water resources in agriculture over an infinite or a sufficiently long finite time horizon. The unit cost of groundwater pumping is a linear function of the drawdown at the pumping site. Optimal groundwater allocations are derived by equating the value of marginal product of groundwater pumped to the pumping cost plus the present value of all dynamic external costs net of return flow credits (social value of the groundwater stocks) over the remainder of the planning horizon. Optimal surface water allocations are derived by equating the marginal value product of surface water to the delivery charge plus the opportunity cost of surface water in the downstream subcatchment less the present value of all dynamic external benefits from irrigation return flows over the remainder of the planning horizon.

The spatial resolution of the efficient prices or the values of groundwater stocks, stream flow and river flow obtained from this solution can provide useful economic insights. The value of groundwater in individual cells is linked to the value of stream water in downstream stream segments while the value of water at the tail end of the stream is linked to the opportunity cost of river water in the downstream subcatchment. Mirroring the state equation for stream flow in the hydrological component, an equation for stream flow values relates the value of water in a stream segment to that of the adjacent downstream segment. This equation is adjusted at each stream segment to account for outflow to (inflow from) the underlying aquifer. The stream water derives economic value from being used for irrigation in the downstream subcatchment (external cost) and through leakages to the aquifer (benefit).

## usefulness for evaluating policy and management options

For each behavioral assumption, for each cell and for each year the model solution provides information on the optimal use of groundwater and surface water. For behavior 2, for each cell and for each year, the model solution also provides information on the private opportunity cost of groundwater stocks and private benefits of return flow. For behavior 3, for each cell and for each year the model solution provides information on both private and social opportunity costs and benefits of groundwater stocks, return flows, stream flows and river flows.

### *optimal allocations*

The optimal groundwater and surface water uses obtained under all three behavioral assumptions can be compared along with the consequent state of the groundwater–surface water system. Such comparisons will highlight the implications or future consequences of no intervention as simulated by behaviors 1 and 2. Given the behavioral assumptions made, water use is expected to be lower with behavior 3 than with behaviors 1 and 2, which do not factor in the social costs of water use. Higher use with behaviors 1 and 2 lead to lower hydraulic head, stream flows and river flows which reduce surface water availabilities to downstream diverters. Optimal water allocations obtained under behavior 3 should be used to guide any review of existing allocations.

### *opportunity costs of resources*

The economic significance of different opportunity cost measures obtained under behavior 3 can be outlined as follows. For each cell and each year the opportunity cost of groundwater measures the benefit bestowed on all pumpers in the following years of a small increase in the groundwater stock resulting from a reduction in pumping in the current year.

An increase in the flow in a stream or river segment from a reduction in pumping groundwater or a reduction in diversion upstream bestows benefits across the downstream reaches. Stream flow and river flow values measure these benefits for a small reduction in pumping and diversion, respectively. The value of water at different points of a stream depends on the effect of outflow to or inflow from the underlying aquifer.

## policy options to improve allocation

The efficient water use and values of groundwater stocks, stream water and river water obtained with behavior 3 can be used to establish the policy settings needed to maximise the value obtained from the use of surface and groundwater resources.

There are a number of policy approaches that can be used to bring current use patterns in line with optimal allocations. These include groundwater and surface water allocations with or without trade, and water use taxes or subsidies. For each farm, the efficient groundwater and surface water allocations can be set at the efficient groundwater and surface water uses obtained under behavior 3. Alternatively, allocations might be set at other levels and made transferable, while ensuring that total allocations cannot exceed the optimal allocation for the jurisdiction. Provided water trade takes place at prices that fully reflect all social costs and benefits, trade can lead to the efficient use of groundwater and surface water.

A third option to aim for efficient use of water is to estimate 'efficient' taxes and subsidies as follows.

- For groundwater, for each cell and year, the efficient tax on pumping can be estimated at the current value of all dynamic external costs net of any return flow credits over the remainder of the planning horizon. For a subcatchment with significant aquifer–stream flow interactions, the efficient tax can be decomposed into two components: a tax based on the net costs on other pumpers across the subcatchment and a tax based on the net costs of lowering hydraulic head beneath the stream bed cells.
- For surface water, if irrigation return flows recharge the aquifer, the benefits due to this recharge partially offset the opportunity cost of surface water downstream. For each cell and year, the efficient subsidy on surface water can be estimated at the current value of all dynamic external benefits over the remainder of the planning horizon. Just as with the efficient tax, the efficient subsidy can be decomposed into two components: a subsidy based on benefits to other pumpers across the subcatchment and a subsidy based on the benefits of raising the hydraulic head beneath stream bed cells.

The above policy options can be evaluated under farm behaviors specified under 1 and 2.

Given the substantial scientific resources required to continuously monitor dynamic hydrological variables and the administrative resources required to implement efficient allocations, the costs and benefits of such measures need to be compared with lower cost, second best options.

# 6

# conclusions

Hydroeconomic models can be useful in choosing the appropriate policy and management options required to maximise the value of water resources. In these models, the net benefits of using water resources are maximised subject to the state of groundwater and surface water systems and institutional arrangements restricting the use of water resources. The state of a water system encapsulates the levels of groundwater and surface water stocks and the process of their flow over space and time. As hydroeconomic models are capable of determining optimal pumping, tax and subsidy levels for a given state of the water system, they can be used as a tool in the adaptive management of groundwater resources. Stochastic aquifer recharge and stream flows mean that the state of a water system evolves over time and that tools that enable adaptive management will be required.

# references

Baumol, W.T. and Oates, W.E. 1975, *The Theory of Environmental Policy*, Englewood Cliffs, N. J, Prentice Hall,

Bredehoeft, J.D. and Young, R.A. 1970, 'The temporal allocation of groundwater –a simulation approach, *Water Resources Research*, vol. 6, no.1, February.

Buras, N. 1963, 'Conjunctive operations of dams and aquifers', *Journal of Hydraulics Division, American Society of Civil Engineers*, HY6, pp. 111–31.

Burt, O.R. 1964a, 'Optimal resource user overtime with an application to groundwater', *Management Sciences*, vol.11, pp. 111-31.

—— 1964b, 'The economics of conjunctive use of groundwater and surface water', Hilgardia, 36, pp. 31–111.

—— 1967, 'Temporal allocation of groundwater', *Water Resources Research*, Vol. 3, pp. 45–56.

Conrad, J. M and Clark, C.W. 1987, *Natural Resource Economics*, Cambridge University Press, England.

Dixon, L.S. 1991, 'Common property aspects of groundwater use and drainage generation' in A. Dinar and D. Zilberman (eds), *The Economics and Management of Water and Drainage in Agriculture*, Kluwar Academic Publication,

Dubert, J.T., Young, R.A and Morel-Seytoux, H.J. 1985, *'Managing and InterRelated Stream-Aquifer System: Economics, Institutions, Hydrology*, Technical Report No. 47, Colorado Water Resources Research Institute, Boulder, Colorado.

Dudley, N.J. Rekils, D.M. and Burt, O.R. 1975, *Reliability, Trade Off and Water Resources Development Modeling*, Discussion Paper 20, Schoool of Economics, University of New South Wales, Kensington, Australia.

Earth Tech Engineering Pty Ltd 2003, *Review of Selected Factors that May Change Future Flow Patterns in the River Murray System*, Report for the Murray Darling Basin Commission, Canberra.

Hafi, A. 2003, Conjunctive use of groundwater and surface water in the Burdekin delta area, ABARE paper presented at the 31st Australian Conference of Economists, Adelaide, 30 Sep—3 Oct.

—— and Cao, L. 2002, Optimal extraction of water from a groundwater system with two linked aquifers, ABARE paper presented at the 46th Annual Conference of the Australian Agricultural and Resource Economics Society, Canberra, 12–15 February.

Knapp, K.C. and Olson, L.J. 1995, 'The economics of conjunctive groundwater management with stochastic surface supplies', *Journal of Environmental Economics and Management*, 28, pp. 340–56.

McDonald, M.G. and Harbaugh, A.W. 1988, *A Modular Three Dimensional Finite-difference Groundwater Flow Model*, U.S. Geological Survey Report 83-875, Washington D.C.

McKinney, D.C. and Savitsky, A. 2003, Basic optimization models for water and energy management (www.gams.com).

Paterson, J. and Keary, J. 1987, *Groundwater Allocation, Policy Setting: The Broad Issue*, Staff Paper 06/87, Department of Water Resources, Melbourne, November.

Provencher, B. and Burt, O. 1994, 'Approximating the optimal groundwater policy in a multiaquifer stochastic conjunctive use setting', *Water Resources Research*, vol. 30, no. 3, March, pp. 833–43.

Young, R.A. 1970, 'The safe yield of aquifers, an economic reformulation', *Journal of Irrigation and Drainage Division*, American Society of Civil Engineering, 96 (IR4), December.

—— Daubert, J.T. and Morel-Seytoux, H.J. 1986, 'Evaluating institutional alternatives for managing an interrelated stream-aquifer system', *American Journal of Agricultural Economics*, vol. 68, no. 4, November, pp. 787–96.

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