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Water rights for variable supplies*

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The relative merits of different systems of property rights to allocate water among different extractive uses are evaluated for the case where variability of supply is important. Three systems of property rights are considered. In the first, variable supply is dealt with through the use of water entitlements defined as shares of the total quantity available. In the second, there are two types of water entitlements, one for water with a high security of supply and the other a lower security right for the residual supply. The third is a system of entitlements specified as state-contingent claims. With zero transaction costs, all systems are efficient. In the realistic situation where transaction costs matter, the system based on state-contingent claims is globally optimal, and the system with high-security and lower security entitlements is preferable to the system with share entitlements.

Key words: property rights, state-contingent claims, water.

1. Introduction

Australian governments, as well as economists, see market trading of secure, transparent and enforceable water rights as a key mechanism for improving the allocation of scarce water between different households, industrial firms, and irrigators (Council of Australian Governments 1994, 2003; Victorian Government 2003, 2004). Already much progress has been made in developing markets to reallocate water between different irrigation uses, particularly for temporary trades within a region (Crase *et al.* 2000; Victorian Government 2004). Water and land rights have been (mostly) unbundled. Water leases have been converted into tradeable rights, and these rights are more precisely and explicitly specified than in the past. Charges for water delivery are based on costs.

The definition of systems of property rights for water that will facilitate permanent as well as temporary trades, trades across regions, and trades across broad user groups is a complex and difficult task. One of the most important difficulties stems from the extreme variability of rainfall in Australia and its effects on the variability of available water for the different uses in any one period and region. Water users have different levels of flexibility in adjusting year-to-year consumption in times of high and low water availability, and different levels of tolerance for uncertainty about supply.

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Different strategies currently used to manage supply variability in specifying property rights for water include: a single entitlement specified as a share of available supplies, either of water released or of water in storage; multiple entitlements with different levels of reliability; and priority rights (Productivity Commission 2003). Young and McColl (2002, p. 29) suggest that a system of priority rights is preferable because it will reduce transactions costs. (Here, and throughout, we use the term ‘entitlement’ to refer to a long-term right to receive an allocation of water, where the allocation received in any year may be contingent on the aggregate availability of water. An entitlement is therefore part of a system of property rights for water.)

A model of state-contingent claims (for example, Chambers and Quiggin 2000) offers a rigorous way of analysing the relative merits of the different options. In this paper, three systems of property rights for water are compared. In the first, variable supply is dealt with through the use of water entitlements defined as shares of the total quantity available. In the second, there are two types of water entitlements, one for water with a high security of supply and the other a low-security right for the residual supply. The third is a system of entitlements specified as state-contingent claims.

With zero transaction costs, all systems are efficient. In a realistic model of the world there are transaction costs in the transfer of entitlements to water and in trade between holders of entitlements under conditions where the water allocation associated with a given entitlement is variable. These costs act as barriers to efficiency-improving trades. In this paper, the transaction costs associated with alternative systems of property rights are compared.

The paper is organised as follows. Section 2 sets out some of the broad issues associated with the allocation of scarce water. Within this general context, a framework for evaluating the different systems of water property rights to accommodate the variability of supplies is presented. The different systems of water property rights are described and their relative attributes are compared and contrasted in Section 3. This comparison is first described informally, using a simple graphical model, and then formally, using the tools of finance theory. Section 4 explains how the model of Section 3 can readily be expanded in more realistic ways. Section 5 provides a model to determine the efficient mix of high-security and lower-security water property entitlements within a system of water property rights based on multiple entitlements with different levels of reliability. Some further institutional issues associated with externalities, water delivery, environmental flows, and the initial allocation of entitlements are discussed in Section 6. Some concluding comments are presented in Section 7.

2. Property rights for water markets

The operations of markets to allocate scarce water in a world of variable supplies (and other changes) requires a system of property rights that captures the social benefits and costs of the alternative uses of water from a reservoir (aquifer or other source). There are at least three important components of social costs for a particular use of water: the opportunity cost of alternative uses of the water at source; costs of treatment and delivery to point of use; and external costs associated with the particular water use. Each of these costs has distinctive characteristics, including geographical location, the form and extent of market failure, and the time period over which costs are incurred.

Differences in geographical location are relevant because most stored water in Australia is some distance from its final use, and in many cases, including for human consumption, water treatment also is required. The distribution and treatment infrastructure is characterised by large and lumpy investments that are location specific, and once committed become sunk costs.

The time at which water is delivered and used is also relevant. In some cases, and particularly at times of peak demand, capacity constraints and the need for rationing limited capacity through scarcity rents can be encountered. Effective property rights for water delivery will need to reflect capacity constraints and might be specified for relatively short time intervals (perhaps as short as a day).

In many cases, the use of water involves external costs. In particular, the use of water for irrigation may result in rising water tables, causing salinity and other problems. One option to deal with these problems in the specification of property rights is to require water users to have a usage licence or use right that includes an externality correction measure. Clearly, details of the use right would vary with the water use, location, and so forth, and sometimes the differences in detail and their implied costs will vary widely to reflect the variation of external costs.

Rights to water may be partitioned into water ownership rights, distribution rights, and use rights. To simplify, we take as given an appropriate system of delivery rights and use rights, and focus on the specification of water ownership rights at the source or at the dam wall. In particular, we explore options for specifying these water rights in the context where water supplies vary because of seasonal conditions from year to year.

As a final introductory point, the paper draws a distinction between an entitlement to water and an allocation of water. An entitlement refers to a long-term or perpetual life property right. An allocation refers to water made available for use over a short interval of time. Permanent water sales refer to the transfer of entitlements and temporary water sales refer to the transfer of an allocation for a particular period. These terms closely relate to the system of corporate capital property rights with the share being the entitlement and the dividend being the allocation. Then, just as the value of the share, an asset, equals the discounted value of the expected stream of future dividend flows, the value of an entitlement, again an asset, equals the discounted expected value of future water allocations.

3. Model

3.1 Basic model

A simple model can be used to compare two systems of water property rights: one with a single entitlement to a share of total available water; and a second that has a high-security entitlement and a lower security entitlement for residual water. In New South Wales, the two entitlements in the second system are referred to as high-security and general security rights, and in Victoria they are referred to as water rights and sales water.

Figure 1 illustrates the operation of an efficient system of water allocation. There are two sets of water demand: low-flexibility uses with a relatively low elasticity of demand denoted by superscript l, shown in Figure 1a; and high-flexibility uses with a relatively elastic demand denoted by superscript h and shown in Figure 1b. Low-flexibility uses include for household indoor use, industry, and perennial crops. High-flexibility uses include gardens and annual crops. These demands are net of delivery costs and any external costs. The two demands sum to give aggregate demand for water, $D = D^h + D^l$, as shown in Figure 1c. There are two states of nature, namely a wet year with supply Q_w which occurs with probability p, and a dry year $Q_d < Q_w$ with probability $1 - p$. These supply quantities are net of allocations for environmental flows.

From Figure 1c we can identify market outcomes that result in an efficient allocation of water. Consider first a wet year. With quantity $Q_w = Q^l_w + Q^h_w$, market price is P_w, and Q^l_w is allocated to low-flexibility uses and Q^h_w to high-flexibility uses. In a drought year, quantity is reduced to Q_d. Market price rises to P_d to ration the reduced supply. The absolute volume allocated to each use falls, and more importantly the relative share of water allocated to more flexible uses falls. In Figure 1c as drawn, the high-flexibility users would purchase zero water in a dry year, and the low-flexibility uses would be allocated $Q^l_d = Q_d$.

Consider now the two different sets of options for specifying property rights, and initially assume a perfectly competitive market with no transactions costs. With the first option where water entitlements are specified as a share of available flows, suppose the rights are allocated to users on the basis of historical average use (a type of 'grandfather' arrangement). Because of competition, and assuming zero transaction costs, arbitrage would ensure a temporary trade price for water of P_w in wet years and P_d in dry years. We can anticipate the need for extensive temporary trades of water, namely, purchases by low-flexibility users from high-flexibility users in dry years, and purchases by high-flexibility users from low-flexibility users in wet years.

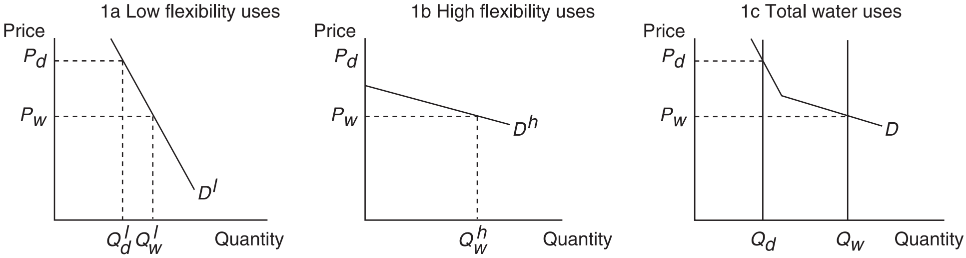


Figure 1 Efficient water allocation and prices.

The expected annual value of the set of share entitlements, V^S, will be

$$V^S = pP_wQ_w + (1 - p)P_dQ_d \tag{1}$$

where p is the probability of a wet year and $(1 - p)$ is the probability of a dry year, P_s are the market prices, and the Q_s are the water quantities received for a share entitlement, for states $s = w, d$. The value of a water entitlement, or of a permanent trade, is then the expected present value of the time series of future year values V^S in Equation (1).

Consider next the second water property rights model which has two entitlements with different levels of supply reliability or security. The high-security entitlement has first priority over water allocated each year, and has an almost complete guarantee of water delivery. The lower-security entitlement is met only after the high-security entitlements have been satisfied. In the context of Figure 1c, the high-security entitlement is for $Q_d = Q^l_d$, which is met with probability one in both dry and wet years, and the lower-security entitlement provides for an allocation of $Q - Q_d$, which is met only in wet years with probability P.

Assuming, as before, a competitive market with zero transaction costs, arbitrage trading will result in a market price of P_w for water in wet years and of P_d for water in dry years. At these prices, the efficient allocation of water shown in Figure 1c for wet and for dry years will occur. The expected annual value of all of the high-security water entitlements, V^H, will be

$$V^H = pP_wQ_d + (1 - p)P_dQ_d \tag{2}$$

and the value of all of the lower-security water entitlements, V^L will be

$$V^L = pP_w(Q_w - Q_d) \tag{3}$$

Note that $V^s = V^H + V^L$. Values for the high-security water entitlements and the lower-security entitlements for permanent trades are the discounted sums of the time series of future values for V^H and V^L in Equations (2) and (3). Per unit of water received, the high-security entitlement is the most valuable, then the water share security entitlement, and the least valuable is the lower-security water entitlement.

Now, compare the property rights system based on a single share entitlement with the system based on two priority entitlements (a high-security entitlement and a lower-security entitlement). Suppose initially a world of zero transaction costs. According to the Coase theorem (1960) and as asserted by Young and McColl (2002), either property rights system will induce mutually beneficial transfers of water allocations so that the efficient distribution and associated prices described by Figure 1 will be achieved.

Transaction costs include the costs of: obtaining information; finding other traders; negotiating mutually beneficial trades; effecting and registering these trades; and enforcing contracts (Williamson 1996; Rao 2002). With the current Watermove market for temporary trades of water in southern Australia, sellers pay a 3 per cent commission, and buyers pay a $A55 flat fee plus a transfer fee of up to $A112 for each transaction (Watermove 2005). This direct cost represents only part of the transaction costs.

The ability and right to use water also depends on the transfer of water delivery rights and the acquisition of a water use right. In most cases these rights involve additional transaction costs (ACIL Tasman 2003; Marsden Jacob and Associates 1999). Because of the geographical dispersion and potentially important disaggregated time dimensions of delivery rights, transaction costs are likely to be significant.

Further, there are a number of government-imposed restrictions on transfers across regions that add to uncertainty for the individual and to transaction costs. The acquisition of use rights for new uses or users currently is subject to uncertain and often costly negotiation with authorities. In addition to the measurable costs noted so far, uncertainty about policy together with uncertainty in the minds of risk averse traders as to whether allocated water can be purchased or sold on the spot market as required adds to transaction costs. These costs rule out some mutually beneficial trades, and imply that the Coase theorem result will not, in general be applicable.

Transaction costs may become smaller once a well-defined set of water property rights is in place and the market has matured. However, in view of the complexity of water rights, transactions costs are likely to remain important. For the foreseeable future, transaction costs are unlikely to be low enough to justify invoking the Coase theorem. It follows that it is desirable to design a system of property rights in such a way as to reduce the need for temporary trades if possible.

The share entitlement system requires a large number of transactions for temporary water transfers. For example, the low-flexibility users can either acquire most entitlements to ensure supply in dry years and sell surplus water in wet years, or they can hold a lesser number of entitlements and buy allocations in the dry years, or some combination. High-flexibility users would be on the other side of the market, selling allocations in dry years and buying in wet years.

By contrast, with the dual system of water entitlements, the low-flexibility users would acquire the high-security entitlements for most of their needs. High-flexibility users would acquire lower-security entitlements. There would be little need for temporary trades to transfer allocations between the two sets of users.

Then, if transaction costs are significant, as seems likely for the reasons noted, the two systems of water property rights will yield different outcomes. In particular, the system with two water entitlements, distinguished by priority, requires less trade in variable water allocations and therefore will result in a more efficient pattern of water allocation in response to variability in water supplies than the apparently simpler property right system based on a single share entitlement.

3.2 Finance theory model

The model presented above can be generalised to allow for a set of water users $i = 1 \ldots I$. We begin by considering the case when there is a fixed aggregate supply Q_w, Q_d with $Q_d < Q_w$. As was first observed by Arrow (1953), the existence of a complete set of state claims, one for each state, freely tradeable without transactions costs, guarantees that a competitive market outcome will be Pareto-optimal. As in the basic model, denote the state-contingent water prices by P_w, P_d and the demand function for user i by $D^i\ (P_w, P_d)$ where D: $\Re^2_{++} \to \Re^2_+$. We assume that, for all $\bar{P}$,

$$\sum_i D^i_w(\bar{P}, \bar{P}) \leq \sum_i D^i_d(\bar{P}, \bar{P}). \tag{4}$$

That is, at any fixed price $\bar{P}$, aggregate demand in the dry state is at least as high as in the wet state. It follows that the market-clearing price vector P^*_w, P^*_d for which

$$\sum_i D^i_s(P^*_w, P^*_d) = Q_s \quad s = 1, 2 \tag{5}$$

must satisfy $P^*_w < P^*_d$.

The analysis above can fruitfully be reconsidered using the tools of state-contingent finance theory.

We consider a model with two states of the world as before, with state 1 being the wet state w, and state 2 being the dry state d. As above, we assume that the (risk-neutral) probability of state w is given by p. Water entitlements may be viewed as bundles of state-claims (q_w, q_d) or, to use finance terminology, water securities. Thus, a secure entitlement of one unit of water would be represented by (1, 1), a low-security entitlement by (1, 0) and a share entitlement by (1, ω) where $\omega = Q_d/Q_w$ is the ratio of aggregate water availability in state d to aggregate availability in state w. These are the main options under review in the policy debate.

A water security structure Σ consists of a set of securities $j = 1 \ldots J$, each of which is characterised by a pay-off vector $\boldsymbol{a}^j = (q_w, q_d)$. We denote by A the associated $J \times S$ pay-off matrix for the securities, with (j, s) entry given by q^i_w. If A is of full rank, there is a 1–1 mapping between security prices, denoted by V^j for security j with pay-off (q^j_w, q^j_w), and the implied supporting state-contingent water prices $P^*_w < P^*_d$ satisfy

$$V^j = pP^*_w q^j_w + (1 - p)P^*_d q^j_1, \tag{6}$$

as in the basic model, where p is, as before, the probability of state w. In this case, the security structure is said to span the state space.

Spanning is a crucial concept in finance theory. If the security structure spans the state space, then any possible set of state-contingent pay-offs (in this case, water allocations) can be constructed as the outcome of a portfolio of marketed securities. Hence, in the absence of transactions costs, the market allocation must, by the First Fundamental Theorem of Welfare Economics, be Pareto optimal.

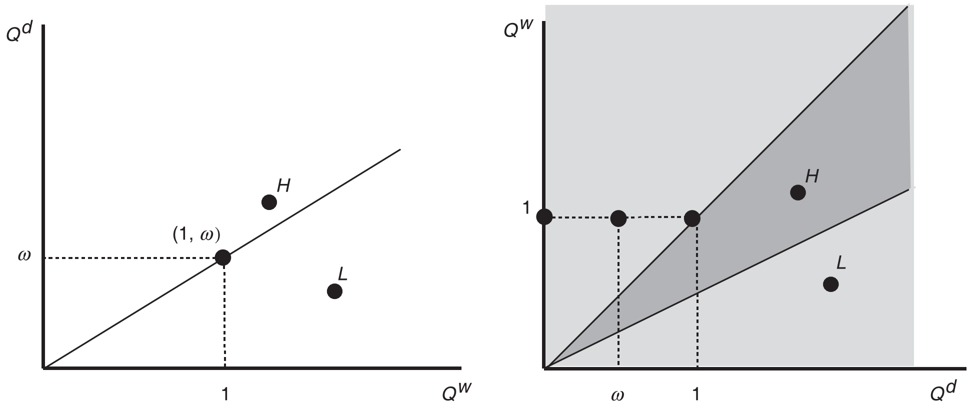
The idea is illustrated in Figure 2 (a,b). The span of the securities concerned is given by the shaded area. The darker shaded area represents pay-off vectors that can be obtained with non-negative holdings of all securities, that is, without shortselling.

Conversely, and for an arbitrary number of states the state-claim prices can be derived from the security prices as

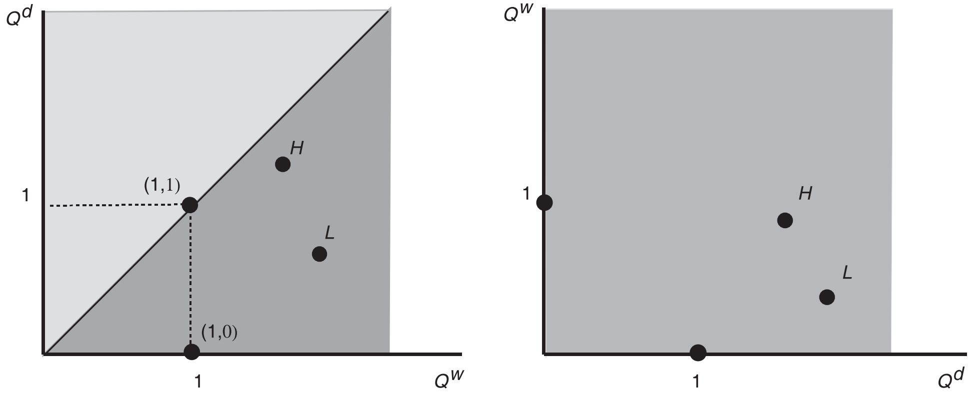
$$\pi^* = A^{-1}\text{v}, \tag{7}$$

where $p^*_s = p_s P^*_s$.

A portfolio is a vector $h \in \mathfrak{R}^J$, where h_j is the holding of asset j. Note that, except where stated otherwise, we allow, $h_j < 0$, that is, short-selling. Given a water security structure Σ, an entitlement q is in the span of Σ if there exists a portfolio h such that $Ah = q$.



a: Asset span for Σ^0 c: Asset span for Σ^2



b: Asset span for Σ^1 d: Asset span for Σ^3

Figure 2 Asset spans for four water security structures.

We first consider the following possible security structures:

Σ^0 consists of a share entitlement (1, ω) only; and

Σ^1 consists of a high-security entitlement (1, 1) and a lower-security entitlement (1, 0).

These securities are illustrated in Figure 2 (a,b), where the axes represent quantities contingent on state w and state d. The share entitlement (1, ω) is marked in Figure 2a, and the entitlements (1, 1) and (1, 0) are marked in Figure 2b. The span Σ^0 is given by the ray through (1, ω). The span of Σ^1, with and without shortselling is given by the shaded areas.

If shortselling is permitted, Σ^1 spans the state space. More generally, under the standard assumptions of finance theory, with two states of nature, no transactions costs and no restrictions on shortselling, any two linearly independent securities span the state space. It follows that, under the stated conditions, Σ^1 spans state space and will permit the achievement of the first best outcome. This gives one reason why the security structure Σ^1, with high-security and lower-security entitlements, will, in general, be superior to Σ^0. Unless desired entitlement is proportional to (1, ω), it will not lie within the span of Σ^0.

The point may be illustrated further by considering the points marked H and L, representing the holdings desired by two water-users, one of whom demands relatively high-security H, with water use in the dry state close to that in the wet state, while the other is willing to accept lower security, that is, greater variability. Under Σ^0, each user gets the same level of security, represented by the ray through (1, ω). By contrast, under Σ^1 the two parties can trade to achieve the desired outcome.

Consideration of standard finance models suggests an additional possibility that may be of interest, at least as a theoretical benchmark. Observing that the lower-security entitlement is a state-claim for state w, we may wish to consider the corresponding state-claim for state d, with return (0, 1). This is a water allocation made available only in the dry state. Such a claim might be of interest to a farmer or urban water user who relied on rainfall in normal years, but who wished to supplement rainfall with irrigation water in dry years (the 'droughtproofing' rationale for irrigation).

Σ^2 consists of a share entitlement (1, ω) and a secure entitlement (1, 1).

Σ^3 consists of state-claims (1, 0) and (0, 1).

Both Σ^2 and Σ^3 span state space, as illustrated in Figure 2 (c,d). Therefore, under the stated conditions, and with no restrictions on short-selling, the security structures Σ^2 and Σ^3 will permit the achievement of the first best outcome. In the absence of short-selling, however, irrigators with desired holding L will not be able to reach this position under Σ^2.

3.3 Temporary trading

Thus far, temporary trades have not been taken into account. A more realistic model, closer to the spirit of the informal discussion above, would begin by excluding short-selling, that is, by restricting attention to portfolios $h \in \mathfrak{R}_+^J$, with $h_j \geq 0$, for all j. It would then be necessary to consider temporary trades as a supplement to holdings of permanent entitlements. In this way, water users with allocations attached to their entitlements that are in excess of their desired consumption in a given year can dispose of them using temporary transfers. Since these temporary transfers take the place of short sales, they are conveniently represented by the negative state claims (–1, 0) and (0, –1). Thus, the issue of such a negative state claim entitlement corresponds to a temporary purchase of water.

More formally, we replace the entitlement structures Σ^0, Σ^1, Σ^2, Σ^3 with structures $\hat{\Sigma}^0$, $\hat{\Sigma}^1$, $\hat{\Sigma}^2$, $\hat{\Sigma}^3$ by imposing the restriction that no short selling is allowed, and adding the temporary transfer entitlements described above. Thus for example, $\hat{\Sigma}^1$ consists of entitlements with payoffs (1, 1), (1, 0), (–1, 0) and (0, –1). For any given Σ, the expanded entitlement structure $\hat{\Sigma}$ consists of J entitlements for which holdings are restricted to be non-negative and S (negative) state claims which may be either bought or sold, for a total of $\hat{J} = J + S$.

With this setup, market participants can achieve any desired bundle of water entitlements by trading in the temporary markets. Trade in the temporary market will not be necessary to achieve a desired entitlement of water $q = (q_w, q_d)$ if q lies in the positive span of Σ, that is, if there exists a portfolio $h \in \mathfrak{R}_+^J$ such that $\Sigma_j h_j a^j = q$.

3.4 Transactions costs

In the absence of transactions costs, the existence of the temporary market would render permanent entitlements to water redundant. The fact that most water users prefer permanent entitlements indicates that transactions costs are significant. In addition, a crucial assumption underlying the result above is that there are no restrictions on short selling. In practice, short selling is not permitted under current market rules and seems unlikely to develop.

The properties of financial market equilibrium with transactions costs and restrictions on short selling have been examined by a number of writers, including Pesendorfer (1995), Prisman (1986) and Ross (1987). The analysis below draws on their work.

We assume that temporary transfers are associated with transaction costs t_w, and t_d and that, in terms of initial incidence, transactions costs are borne by the purchaser of water, that is by the issuer of negative state claims. More precisely, given a state-claim price vector (p_w, p_d), the issuer of a state claim yielding –1 in state s pays $(p_s + t_s)P_s$ but the purchaser receives only $p_s P_s$. Note that, in equilibrium, the incidence of transactions costs will be shared by buyers and sellers, so that the equilibrium state-claim price vector with transactions costs $(\hat{p}_w, \hat{p}_d)$ will not, in general, be equal to the first-best equilibrium vector (P_w^*, P_d^*).

Thus a comparison between a share entitlement system and a system with two water entitlements may appear to be biased against the share entitlement system, which does not span the state space. We will show, however that the arguments set out above will hold even if we consider a combination of shares and high security entitlements.

We may observe that these entitlements will never be needed if the water entitlements take the form of state claims, since the first best allocation can always be achieved without short-selling. The arguments presented above can be formalised to show that transactions costs will always be lower in case (ii) (a high-security entitlement and a lower-security entitlement) than in case (i) (a share entitlement and a high security entitlement).

For any water entitlement $Q = (Q_w, Q_d) \in \Re^2_+$, let $t^i(Q)$ be the vector of transactions costs associated with the purchase of Q under security structure $\hat{\Sigma}^i$. As an example, consider an individual with access to a share entitlement and temporary transfers, who wishes to hold the equivalent of a high security entitlement, so that $Q_w = Q_d$. A high security entitlement may be constructed by purchasing $1/\omega$ units of the share entitlement and $[(1/\omega) - 1]$ units of the negative state claim $(-1, 0)$ (that is, selling the undesired $(1/\omega) - 1$ units of water in wet states on the temporary transfer market). Relative to the first-best, the associated transaction cost incurred in state w is $t_w[(1/\omega) - 1]$. No transactions costs are incurred in state d. More generally, we may derive the following characterisation of state-contingent transaction costs for any choice of allocation Q and for each of the four securities structures, $\hat{\Sigma}^0$, $\hat{\Sigma}^1$, $\hat{\Sigma}^2$, $\hat{\Sigma}^3$:

$$
\begin{array}{ll}
t^0(Q) = \begin{array}{l} \left(t_w\left(Q_w - \dfrac{Q_d}{\omega}\right), 0\right) \\ (0, t_d(Q_d - \omega Q_w)) \end{array} & \begin{array}{l} Q_d < \omega Q_w \\ Q_d \geq \omega Q_w. \end{array} \\[2ex]
t^1(Q) = \begin{array}{l} (0, 0) \\ (0, t_d(Q_d - Q_w)) \end{array} & \begin{array}{l} Q_d < Q_w \\ Q_d \geq Q_w. \end{array} \\[2ex]
t^2(Q) = \begin{array}{l} (0, 0) \\ \left(t_w\left(Q_w - \dfrac{Q_d}{\omega}\right), 0\right) \\ (0, t_d(Q_d - Q_w)) \end{array} & \begin{array}{l} \omega Q_w \leq Q_d \leq Q_w \\ Q_d < \omega Q_w \\ Q_d > Q_w. \end{array} \\[2ex]
t^3(Q) = (0, 0) & \forall\, Q.
\end{array}
\tag{8}
$$

Since these transactions cost vectors share a common ranking for all Q, we obtain our main result.

Theorem 1 *Consider the alternative security structures* $\hat{\Sigma}^1$, $\hat{\Sigma}^2$, $\hat{\Sigma}^3$. *Then, for any* Q, $t^0(Q) \geq t^2(Q) \geq t^1(Q) \geq t^3(Q) = 0$, *where the inequality is interpreted in vector terms.*

Thus, the intuition derived from the graphical model is borne out by a formal analysis. For any given Q, the share entitlement system involves transactions costs that are always at least as high as, and sometimes strictly higher than, a system of high-security and lower-security entitlements. The first-best is obtained under the complete system of contingent state-claims $\hat{\Sigma}^3$. Note that, since Q is endogenous, Theorem 1 does not necessarily imply that greater transactions costs are necessarily incurred under structure $\hat{\Sigma}^2$ than under $\hat{\Sigma}^1$. It may be, for example, that costs are so high as to preclude trade altogether. More generally, depending on the structure of transactions costs, the volume of trade may be lower under $\hat{\Sigma}^2$ than under $\hat{\Sigma}^1$. With the simple setup here, however, this should not arise. Since the gains from trading away from the initial allocation are greater under $\hat{\Sigma}^2$, there should be more trade and higher transactions costs under $\hat{\Sigma}^2$ than under $\hat{\Sigma}^1$.

4. Extensions

It is straightforward to enrich the simple model of Section 3 with a number of features of practical importance without altering the main conclusions on the operation of, and the relative merits of, the two sets of options for specifying water property rights where the variability in water supply availability is important.

4.1 Many users and many states

The two sets of water users in Figure 1 may be extended to include any number of user types by adding to the number of panels for different user categories. Further disaggregation of users is warranted when shapes of net water-demand curves, and especially their elasticities of demand, differ significantly between user categories. Typically, this will require the specification of more than two states of nature.

The model presented above depicts the case of a single river with one dam. In reality, there may be several tributaries, multiple dams, or even the need to recognise interdependence of groundwater and surface water supply sources as part of a water catchment and allocation system.

Consider a water catchment with several tributaries and dams and initially examine the case of interconnected users where the different users directly or indirectly can access the different water sources. Arbitrage trading among the different water users, or at least of marginal users at the end of the water catchment, will mean a common price for all water allocations in each period. Such arbitrage opportunities would arise for those periods or states of water supplies in which the different users in the catchment are able to draw water from a common pool; or more generally, with a system of multiple tributaries with their own dams and where main stream water users can draw on water from each of the dams.

When dams are assigned water entitlements with different degrees of allocation security, expressions for the expected value of the different entitlements can be derived as for the earlier models. Then, water entitlements for the different dams could have different values depending on the probabilities on the quantities of water allocated per entitlement and on the market water prices associated with the water allocation in each state.

4.2 Changes in demand

Changes in demand conditions, particularly as they alter the relativities between the different uses, and changes in the aggregate available supply will be reflected in changes in relative (and absolute) prices of the annual water prices used to coordinate temporary trades, and then onto changes in the values of the two property entitlements (via Equations 2 and 3), which co-ordinate changes in the allocation of permanent water use entitlements. Changes in the relative prices of water flows and changes in the relative asset prices signal changes in the relative merits of different water uses. In turn, water is reallocated from the now relatively lower-valued to higher-valued uses.

Compared with the option of a single asset market for water share entitlements, the multiple product option means a thinner market for each product although there is a high level of substitutability and therefore interdependence, and some extra market administration and associated higher transaction costs. Although this is ultimately an empirical question, these potential downsides seem likely to be small in comparison with the large number of trades required under the share entitlement system of property rights. Many of these trades would be avoided under a system with high-security and lower-security entitlements.

5. Choice of mix of water categories

A simple model with a product transformation frontier and a map of preference indifference curves in expected annual allocations of water can be used to determine the efficient allocation of available water between the high-security and lower-security water entitlements. The model also shows how changes in the relative entitlement prices and a market can be used to change the mix of entitlements over time in response to inevitable but very difficult to predict changes in future market circumstances.

Figure 3 illustrates the production possibility frontier. On the two axes are the expected allocation of water per period from each of the two water entitlements, high security, $E(Q^h)$, and lower security, $E(Q^l)$. The production possibility frontier is shown as the concave function. It is based on hydrological information, and reflects the fact that reallocating water from lower-security to high-security property rights requires additional storage between seasons. Storage will result in losses of water to evaporation, seepage, and overflow spillages during very wet periods, so the frontier will have a slope $-\infty \leq [dE(Q^l)/dE(Q^h)] \leq -1$. Aside from these general properties, the particular position and shape of the production possibility frontier is dam specific and will depend on rainfall variability, temperatures, winds, and the ratio of volume-to-surface area.

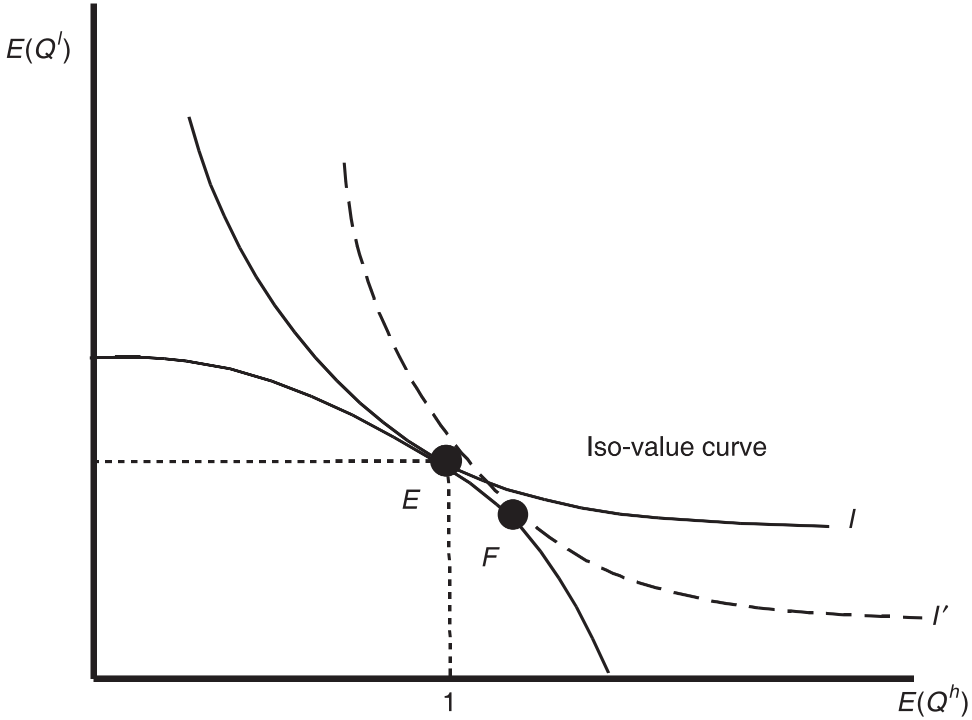


Figure 3 Efficient mix entitlements.

Water user preferences for the two types of water entitlements are given by the convex indifference or iso-value curve, which belongs to a family of preference curves. Normally, the indifference curve will be strictly convex due to transactions costs, and because water users are risk averse. In the exceptional case of zero transaction costs, no risk aversion and no storage losses, the two entitlements could be regarded as perfect substitutes (per expected unit of water) with a slope

$$\frac{dE(Q^1)}{dE(Q^h)} = -1. \tag{9}$$

Then, for the normal preference curves, the efficient mix of high-security and lower-security water entitlements will be an internal one, at point E in Figure 3, with the prices per unit of expected water per entitlement at the tangency point with $(P^l/P^h) < 1$.

Changes in market circumstances will alter the shape of the family of preference curves. For example, in Figure 3 the indifference curve is shown as shifting from I to I' and becoming steeper. The marginal rate of substitution between the high-security and lower-security water entitlements is likely to increase with increases in risk aversion, transactions costs, the cost of risk management strategies, and the relative profitability of the water uses with inflexible demand. Such a change in preferences then would require a reallocation of water between high-security and lower-security water entitlements. In Figure 3, the shift in preferences from *I* with equilibrium at *E*, to the preference set with indifference curve *I′*, requires a reallocation to *F*, and an increase in the relative price of high-security water entitlements.

Given a shift in demand, a profit-maximising water authority will benefit from the reallocation needed to achieve the shift from *E* to *F*, or, more generally, any equilibrating change in the mix of high-security and lower-security water entitlements. To illustrate, for the shift from *E* to *F*, the water authority would purchase lower-security entitlements and sell high-security entitlements at a price ratio given by the marginal rate of technical substitution on the production possibility function, and noting that this price ratio is bounded by the relative market equilibrium prices at *E* and *F*.

These transactions generate a profit for the water authority. Hence, under competitive conditions, profit incentives for the water authority and competitive market prices for the different types of water entitlements will facilitate dynamic efficiency reallocations of the mix of high-security and lower-security entitlements in response to changes in market circumstances facing the different uses and users of water.

In practice, however, most water authorities are natural monopolies. The use of market forces to reallocate the mix of types of water entitlements in response to changing market conditions therefore would require that the procedures used by the water authority be fully explained, explicit, transparent, and subject to independent scrutiny.

6. Other institutional issues

This section discusses some institutional options important for the wider market context in which the special model of the earlier section was developed. In particular, it considers externalities, water delivery, environmental flows, and the initial allocation of water property rights. These issues are beyond the scope of the present paper, but need to be addressed in a more general consideration of water allocations.

Many of the extractive uses of water involve external costs. Some are largely of point source pollution form, such as sewage and industrial waste disposal, and others are of the more difficult to measure non-point source pollution form, such as chemical residues and downstream salinity from augmentation of the water table and from run-off water from irrigation. One policy strategy to internalise these externalities is to impose conditions on water use licenses (Young and McColl 2002). That is, a licence specifying conditions on water use may be employed as a targeted instrument for externalities.

Water delivery costs, and any physical restrictions on water delivery, also can be tied to the water use licence. Alternatively, separate markets for water delivery access rights might be established. For either option, the relevant time interval may be as short as a day, compared with the normal market period for water rights, which is an irrigation season. Economic efficiency requires that the charges and other conditions of water delivery should vary with time, region, location, capacity utilisation, seepage and evaporation rates, and other factors.

Most extractive uses of water by households, industry, and government have private-good properties of rival consumption and low costs of exclusion, and therefore are readily amenable to market allocation. By contrast, many of the values to society derived from flora, fauna, amenity, and heritage services produced with water allocated to the environment have public good properties. Unregulated markets will allocate too little water for environmental flows (Freebairn 2003).

A final issue concerns the initial allocation of property rights for water. From the perspective of efficiency, the Coase theorem indicates that trade from any initial starting allocation will lead to an efficient allocation in the long run (Coase 1960). The current reality is that, in most cases, available water is fully allocated, if not over-allocated, and existing users perceive that they own the water rights, even though the legal basis for the perception is fuzzy at best (Goddin 2003). In these circumstances, widely held views on distributional equity favour a 'grandfather' arrangement whereby the new property rights are allocated to current users.

In cases of over-allocation, or where water is to be reallocated from extractive uses to environmental flows, reductions in usage could be achieved without violating rights, by government purchase of rights or by specifying the rights to have a schedule of declining entitlements to water in the future. A further option would be for governments to purchase reversion rights when current licenses expire (Quiggin 2006).

7. Conclusions

In this paper, we have examined alternative options for defining property rights for water where the aggregate availability of water at the dam or source is variable because of rainfall volatility. One option specifies an entitlement system based primarily on a share allocation, in which water allocations are measured as a share of the available supply. The second option has two water entitlements, a secure right providing a highly reliable supply, and a lower-security right for the residual water, which has a lower level of reliability. A third option, considered primarily as an analytical benchmark, is based on state-contingent claims for water.

Under the special assumptions of zero transaction costs and competitive market behaviour, all systems of water rights for managing variability of water supply generate identical market outcomes, and these outcomes result in an efficient allocation of scarce water among different extractive uses. These results are an instance of the Coase theorem.

In practice, the assumption of zero transaction costs is unreasonable for the water market. The share entitlement system of property rights requires more trading of temporary water than will the model based on high-security and lower-security entitlements. Under a share entitlement system, high-value water users with relatively inelastic demands for water are net buyers of water in dry years, and net sellers in wet years; the opposite is true for users with relatively elastic demands for water.

By contrast, with high-security and lower-security entitlements, the high-value and relatively inelastic demand users hold the high-security water entitlements that provide a reliable steady flow of water with little need for purchases and sales as the available water supply varies. Other users with relatively elastic demands access water with their lower-security entitlements mainly in wet years when water is relatively lower priced. The higher transaction costs of the share model include not only the costs of negotiating and registering temporary water sales and purchases, but also the costs of risk management, buying and selling delivery rights, and in some cases, obtaining use licenses.

This point has been illustrated using a model of asset valuation in financial markets with transactions costs. The benchmark is a system of property rights in which there is a complete set of state-contingent claims, which spans the market without the need to allow short-selling. Hence, under the assumptions set out in the model, this system involves zero transactions costs. It is shown that the alternative systems can be ranked, with the system of high-security and lower-security rights having strictly lower transactions costs than a share-entitlement system, even when the latter system is supplemented by a secure entitlement.

The efficient mix of the high-security water entitlement and the lower-security entitlement can be determined by equating relative market prices for the two water rights with the marginal rate of transformation of technical supply of the two water rights. Further, a profit-maximising water authority has a socially efficient incentive to change the mix by buying and selling the two types of water rights in response to changes in market conditions that alter the relative market prices of the water entitlements.

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