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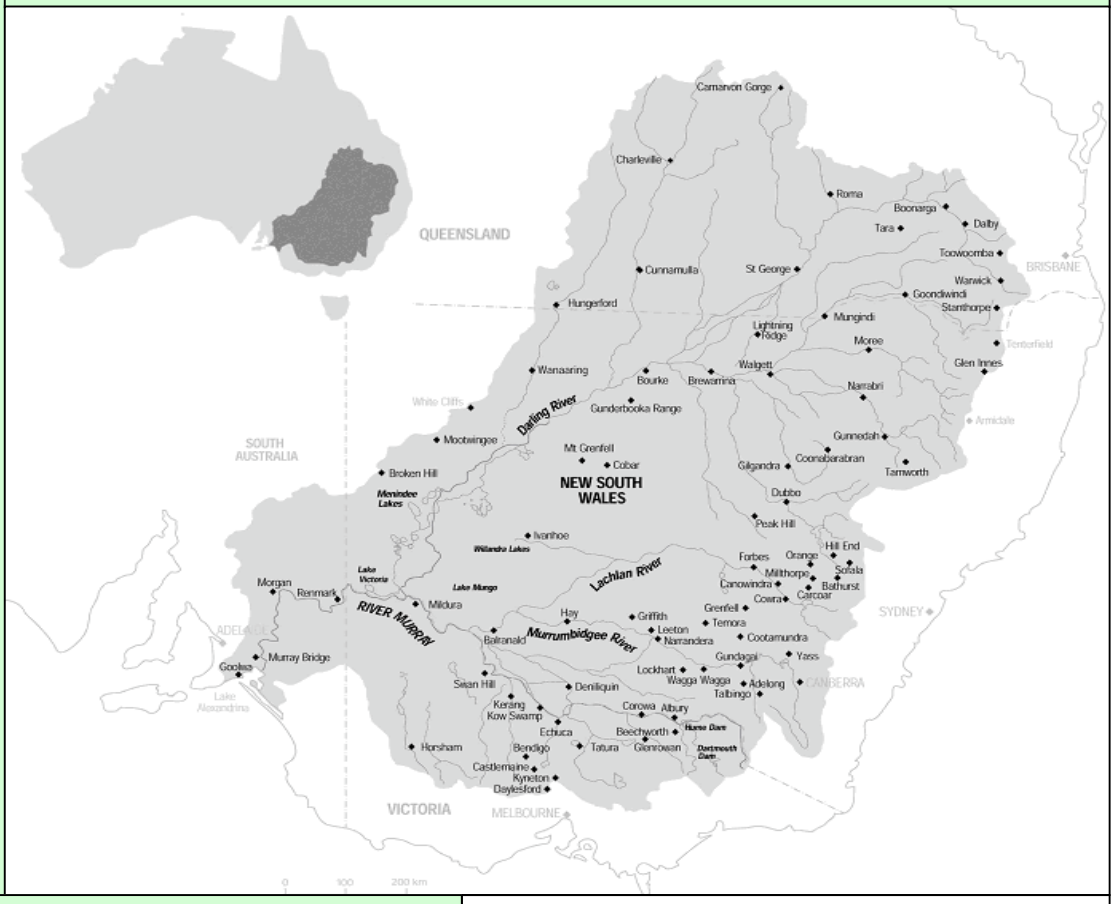

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Water Rights for Variable Supplies

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Abstract

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

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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, together with some direct government intervention for an allocation for environmental flows (see, for example COAG, 1994 and 2003, and Victorian Government, 2003 and 2004). A particularly difficult issue in defining water rights which will facilitate permanent as well as temporary trades, trades across regions, and trades across broad user groups 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. Further, these different water users have different levels of flexibility and tolerance in adjusting year to year consumption in times of high and low water availability. Different strategies currently used to recognise supply variability in specifying property rights for water include a single product specified as a share of available supplies, either of water released or of water in storage, multiple products with different levels of reliability, and priority rights (see, for example, Productivity Commission, 2003). 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. This paper compares and contrasts a system of water property rights based on the share idea, a system based on the idea of two products with different levels of supply guarantee or reliability, and a system based on the idea of state contingent claims.

In a realistic world there are transaction costs in the transfer of water allocations and many water users are risk averse, and these facts act as barriers to efficiency trades. For these circumstances the paper argues in favour of a system of property rights with different levels of supply reliability or of state contingent claims over the simpler system of a single property right expressed as a share of the available water supply. The paper then employs a model based on a hydrological product transformation frontier and an iso-value curve to assess the mix of water property rights, or entitlements, with different levels of supply reliability, and how this mix would change with changes in market circumstances.

The rest of the paper is organised as follows. Section 2 sets out some of the broad issues and context for allocating scarce water, and within this general context it sets a narrower and specific setting for evaluating the

different options for specifying water property rights to accommodate the variability of supplies. The different systems of water property rights are described and their relative attributes are compared and contrasted in Section 3 using a simple graphical model and a more formal treatment 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 priority water property rights. Some further institutional issues associated with externalities, water delivery, environmental flows and the allocation of entitlements are discussed in Section 6. Section 7 provides conclusions.

2 Property Rights for Water Markets

Effective markets to allocate and reallocate scarce water in a world of variable supplies (and other changes) require a system of property rights that capture all 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, any external costs associated with the particular water use. Each of these cost items has distinctive characteristics and they mean a range of feasible property right systems might be adopted.

The beneficial uses of water can be placed into two categories as they relate to the workability of water markets. Commercial uses of water for household consumption, industry and irrigation have private good properties which are important for market allocations. By contrast, some of the uses of water for environmental flows to protect biodiversity and heritage have public good properties for which markets fail. An appropriate allocation of water to environmental flows (to equate marginal social benefit with the commercial water use price) might be effected by caps on uses of water for commercial purposes, by taxes on commercial uses, or by direct government allocation of property rights to an environmental authority. In reality, with changing circumstances the optimal allocation to the environment also will change over time. Our focus is restricted to property rights for the market for commercial uses of water.

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. 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 likely will need to reflect capacity constraints and be specified for relatively short time intervals (perhaps as short as a day). By contrast, the water supply availability interval could be as long as a season or year. Water losses during transmission could be treated as a component of the social costs of water delivery. Then, social costs of water delivery are likely to vary with reference to time, by location and distance from the prime water storage, and according to the capacity of the infrastructure relative to demand.

In many cases the use of water involves external costs, for example sewage disposal and additions to the water table causing salinity and other problems. Policy options to internalise these external costs include the creation of property rights, regulations, taxes, or tradeable permits. Preferably each option would be directed to the pollutant, but sometimes because of measurement and administrative difficulties it would be applied on the water input, production process or related output. One option 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.

Then, to use water requires the holding of a water right, a distribution right and a use right. The Victorian White Paper (2004), for example, proposes that these three categories of property rights be separate rights. Other options include various combinations of a joint water right plus delivery right plus usage right. Given the different dimensions of each category of property right, including differences in time intervals and by location, a system of rights that includes the water plus delivery plus use dimensions would require a very large number of diverse rights. To simplify, this paper takes as given an appropriate system of delivery rights and use rights, and focuses on the specification of water rights at the dam wall. In particular, our interest is in exploring options for specifying these water rights in the context where 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. 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. Unfortunately, a range of other terms as well as these are found in different parts of the Australian (and world) water industry, and this adds to confusion. Permanent water sales refer to the transfer of entitlements and temporary water sales refer to the transfer of an allocation for a particular period.

3 Model

3.1 Basic Model

A relatively simple model can be used to compare a water property right system with a single share of water with a system that has a high security right and a lower priority right for residual water. In NSW these two entitlements are referred to as high security and general security rights, and in Victoria they are referred to as a water right and sales water. Figure 1 provides the details for a particular year and 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.[1] 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

[1]Strictly speaking, the derivation of the demand curves would require a multi-period optimisation problem with probability distributions for prices of water across the different possible states.

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, market price is P_w, and Q_w^l is allocated to low flexibility uses and Q_w^h to high flexibility uses. In a drought year quantity is reduced to Q_d. Market price rises to P_d to ration the reduced supplies. The absolute volume allocated to each use falls, and more importantly the relative share of water allocated to the 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 $Q_d^l = Q_d$.

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 property rights 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 zero transaction costs, in each year arbitrage would ensure a common water, or temporary trade, price 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.[2] The expected annual value of the set of share allocation rights, 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 property right, 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 (1).

Consider next the second water property rights model with two entitlement products with different levels of supply reliability or security. The high security right has first priority and has an almost complete guarantee

[2]A user with an inelastic water demand might adopt one of two extreme strategies for managing water, or any combination of these two. One extreme is to hold enough water rights to guarantee water in the very dry years and to sell surplus water in the wet years. The other extreme is to hold just enough rights for water in wet years and to purchase water in dry years. Those with relatively elastic demands could follow similar, but reverse, strategies.

of water delivery[3], whereas the lower priority entitlement is met only after the high security rights have been met. In the context of Figure 1c, the high security right is for $Q_d = Q_d^l$, which is met with probability one in both dry and wet years, and the lower security right is for $Q - Q_d$, which is met only in wet years with (risk-neutral) probability p_w.[4]

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 rights, V_H, and of all of the lower security water rights, V_L, will be

$$\begin{aligned} V_H &= p_w P_w Q_d + (1 - p_w) P_d Q_d \\ V_L &= p_w P_w (Q_w - Q_d). \end{aligned} \tag{2}$$

Note that $V_S = V_H + V_L$. Values for the high security water rights and the lower priority rights for permanent trades are the discounted sums of the time series of future values for V_H and V_L in (2) and (3). Per unit of water received, the high security right is the most valuable, then the water share security right, and the least valuable is the lower security water right.[5]

Now, compare the single water share property right system with the two water share property right system (a high security right and a lower priority right). Suppose initially a world of zero transaction costs. According to the Coase theorem (1960) and as asserted by Young and McColl (2002), either property right system will induce mutually beneficial transfers of water allocations so that the efficient distribution and associated

[3]Clearly there is a trade-off between the volume which can be allocated to the high security right and its associated level of reliability. From the later discussion on the importance of portfolio choices over the mix of high security and low security water rights, it is desirable that the high security rights have a high probability of supply. For practical purposes a probability greater than 95 per cent is desirable.

[4]In general, there will not exist a known objective probability and it is necessary to focus attention on subjective probability judgements revealed by markets. The risk-neutral probability of s is the probability implied by asset market equilibrium. More precisely, it is the price of state-contingent claims in an Arrow–Debreu equilibrium, normalised so that the sum of all state-claim prices is equal to 1.

[5]For example, if the water market prices P_w and P_d are stable over time, the average price per unit of water received under the V_H, V_S and V_L water rights are, respectively: $pP_w + (1-p)P_d > pP_w + (1-p)P_d(Q_d/Q) > P_w$.

prices described by Figure 1 eventuates. However, the single water share system inevitably requires a much larger number of transactions, although these will be of allocations or temporary water transfers rather than of entitlements or permanent 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. By contrast, with the dual system of water property rights, for the most of their needs the low flexibility users would acquire the high priority rights and high flexibility users would acquire the lower priority entitlements, and there would be little need to transfer allocations between the two sets of users with variability of water supply.

But, in reality transaction costs are unlikely to be low enough to justify invoking the Coase theorem. Transaction costs include the costs to seek information, to find other traders, to negotiate mutually beneficial trades, to effect these trades, to register the trades and to enforce contracts (as described, for example, in Williamson, 1999). In the case of a homogeneous product water at the dam wall, transaction costs may become small once a good set of water property rights are in place and the market has matured. However, the ability and right to use water also depends on the transfer of water delivery rights and the acquisition of a water use right. Because of the geographical dispersion and potentially important disaggregated time dimensions of delivery rights, including their price, transaction costs here are likely to be significant. Further, currently there are a number of government imposed restrictions on transfers across regions which 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 that water can be purchased or sold as required adds to transaction costs which rule out some mutually beneficial and economic efficiency improving trades which underlie the Coase theorem result.

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 sets of property rights requires less transactions of the 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 single share water property right system. Young and McColl (2002, p. 29) make this same point but without explanation. This analysis also points to specifying the high security entitlement, and thereby limiting its quantity, to have a very high probability of delivery of allocation, and typically in excess of 95%. Further, only two entitlement rights distinguished by degree of reliability of supply of water allocations are required. Then, individual users are free to choose the combination of high security and lower priority rights, subject to market clearing prices (discussed below), which maximises their particular needs as they are determined by their particular water using activities and their flexibility and costs of adjustment to the variability of supplies, their attitudes to risk, available risk management strategies, and transaction costs.

Changes in demand conditions, and especially changes causing differential shifts of the demands of different water users, changes in the aggregate water supply available for commercial uses (including the effects of changes in water allocated for environmental flows and potentially climate change), and changes in transaction costs, attitudes to risk and available risk management strategies, will be reflected in changes initially in the prices of allocated water each period and then to changes in the prices of the water entitlements. These price changes then signal and coordinate the reallocation of water from uses of declining relative value to uses of increasing relative value.

3.2 Finance theory model

The model presented above can be generalised to allow for a set of water users $i = 1...I$. 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 $D^i : \Re^2_{++} \rightarrow \Re^2_+$. We assume that for all $\bar{P}$

$$\sum_i D^i_w(\bar{P}, \bar{P}) \leq \sum_i D^i_d(\bar{P}, \bar{P}). \tag{3}$$

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

$$\sum_i D_s^i(P_w^*, P_d^*) = Q_s \; s = 1, 2 \tag{4}$$

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 rights may be viewed as bundles of state-claims (q_w, q_d) or, to use finance terminology, water securities. Thus, a secure allocation of one unit of water would be represented by $(1, 1)$, a low-security allocation by $(1, 0)$ and a share allocation by $(1, \omega)$ 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 $j = 1...J$, each of which is characterised by a payoff vector $\mathbf{a}^j = (q_w, q_d)$. We denote by A the associated $J \times S$ payoff matrix for the securities, with (j, s) entry given by q_w^j. If A is of full rank, there is a 1-1 mapping between security prices, denoted V^j for security j with payoff (q_w^j, q_w^j), and the implied supporting state-contingent water prices (P_w^*, P_d^*) satisfy

$$v^j = p_w P_w^* q_w^j + (1 - p_w) P_d^* q_1^j, \tag{5}$$

as in the basic model, where p_w is, as before, the probability of state w (or, more generally, the unit price of state w contingent claims).

Conversely, the state-claim prices can be derived from the security prices as

$$\boldsymbol{\pi}^* = A^{-1}\mathbf{v}, \tag{6}$$

where $p_s^* = p_s P_s^*$.

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

We first consider the following possible security structures:

Σ^0 consists of a share allocation $(1, \omega)$ only; and

Σ^1 consists of a high-security allocation $(1,1)$ and a lower-priority allocation $(1,0)$;

These securities are illustrated in Figures 2a and 2b, where the axes represent quantities contingent on state w and state d. The share allocation $(1,\omega)$ is marked in Figure 2a, and the allocations $(1,1)$ and $(1,0)$ are marked in Figure 2b. The span of Σ^0 is given by the ray through $(1,\omega)$. The span of Σ^1 is given by the shaded area. The darker shaded area represents payoff vectors that can be obtained without shortselling. It is easy to see that, if short selling 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 short selling, any two linearly independent securities span the state space. It follows that, under the stated conditions, Σ^1 spans the 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-priority entitlements, will, in general, be superior to Σ^0. Unless the desired allocation is proportional to $(1,\omega)$, 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 priority, that is, greater variability. Under Σ^0, each user gets the same level of security, represented by the ray through $(1,\omega)$. 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-priority allocation 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 wished to supplement rainfall with irrigation water in dry years (the 'droughtproofing' rationale for irrigation).

Σ^2 consists of a share allocation $(1,\omega)$ and a secure allocation $(1,1)$.

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

It is easy to see that both Σ^2 and Σ^3 span the state space. 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 $\mathbf{h} \in \Re_+^J$, 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 $\Sigma^0, \Sigma^1, \Sigma^2, \Sigma^3$ 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, it is obvious that market participants can achieve any desired bundle of water allocations by trading in the temporary markets. Trade in the temporary market will not be necessary to achieve a desired allocation of water $\mathbf{q} = (q_w, q_d)$ if $\mathbf{q}$ lies in the positive span of Σ, that is, if there exists a portfolio $\mathbf{h} \in \Re_+^J$ such that $\Sigma_j h_j \mathbf{a}^j = \mathbf{q}$.

3.4 Transactions costs

In the absence of transactions costs, the existence of the temporary market would render permanent rights to water redundant. The fact that most water users prefer permanent rights 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 allocation system and a system with two water entitlements may appear to be biased against the share allocation 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 rights 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 the case (ii) (a high-security allocation and a lower-priority allocation) than in case (i) (a share allocation and a high security allocation).

For any water allocation $\mathbf{Q} = (Q_w, Q_d) \in \Re^2_+$, let $\mathbf{t}^i(\mathbf{Q})$ be the vector of transactions costs associated with the purchase of $\mathbf{Q}$ under security structure $\hat{\Sigma}^i$. As an example, consider an individual with access to a share allocation and temporary transfers, who wishes to hold the equivalent of a high security allocation, so that $Q_w = Q_d$. A high security allocation may be constructed by purchasing $\frac{1}{\omega}$ units of the share allocation and $\left(\frac{1}{\omega} - 1\right)$ units of the negative state claim $(-1, 0)$ (that is, selling the undesired $\frac{1}{\omega} - 1$ 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 $t_w \left(\frac{1}{\omega} - 1\right)$. 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 $\mathbf{Q}$ and for each of the four securities structures, $\hat{\Sigma}^0, \hat{\Sigma}^1, \hat{\Sigma}^2, \hat{\Sigma}^3$:

$$\mathbf{t}^0(\mathbf{Q}) = \begin{array}{ll} \left(t_w\left(Q_w - \frac{Q_d}{\omega}\right), 0\right) & Q_d < \omega Q_w \\ (0, t_d(Q_d - \omega Q_w)) & Q_d \geq \omega Q_w. \end{array}$$

$$\mathbf{t}^1(\mathbf{Q}) = \begin{array}{ll} (0,0) & Q_d < Q_w \\ (0, t_d(Q_d - Q_w)) & Q_d \geq Q_w. \end{array}$$

$$\mathbf{t}^2(\mathbf{Q}) = \begin{array}{ll} (0,0) & \omega Q_w \leq Q_d \leq Q_w \\ \left(t_w\left(Q_w - \frac{Q_d}{\omega}\right), 0\right) & Q_d < \omega Q_w \\ (0, t_d(Q_d - Q_w)) & Q_d > Q_w. \end{array}$$

$$\mathbf{t}^3(\mathbf{Q}) = (0,0) \ \forall \ \mathbf{Q}. \tag{7}$$

Since these transactions cost vectors share a common ranking for all $\mathbf{Q}$, we obtain our main result.

Theorem 1 *Consider the alternative security structures* $\hat{\Sigma}^1, \hat{\Sigma}^2, \hat{\Sigma}^3$. *Then, for any* $\mathbf{Q}$,

$$\mathbf{t}^0(\mathbf{Q}) \geq \mathbf{t}^2(\mathbf{Q}) \geq \mathbf{t}^1(\mathbf{Q}) \geq \mathbf{t}^3(\mathbf{Q}) = \mathbf{0},$$

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 $\mathbf{Q}$,[6] the share allocation system involves transactions costs that are always at least as high as, and sometimes strictly higher than, a system of high-security and lower-priority rights. The first-best is obtained under the complete system of contingent state-claims $\hat{\Sigma}^3$.

[6]Note that, since $\mathbf{Q}$ 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 the users is warranted when the shapes of the net water demand curves, and especially their elasticities of demand, differ significantly between the 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 example, 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; or less generally, for those periods or states of water supplies in which the different users in the catchment are able to draw water from what effectively is a common pool. If each dam is assigned a water entitlement, or of different 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, the value of 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.

The story is more complicated for those situations in which the water

market is not interconnected for all states, but it is for some. An example is when all water from a dam on a particular tributary is used along that tributary in a dry spell, but in more normal times some water also flows into the main stream. Then, water prices in the dry spell will not be the same across the system; in fact, prices for water in the (temporary) not-connected tributary will exceed prices for other parts of the system. Then, there is another source of variation effect on the value of water entitlements associated with the non-uniform market prices of water allocated in different periods. This is not a problem for numerical modelling, and neither will it alter the main conclusion of the earlier models of Section 3 that in practice a system of multiple water entitlements with different levels of supply reliability is preferable to a single water share entitlement.

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 rights (via equations (2) and (3)) which coordinate changes in the allocation of permanent water use rights. In particular, these 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, and especially with respect to their flexibility to adjust to the high variability of available water supplies. Compared with the option of a single asset market for water share rights, 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. While 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 single product share model described above which would be avoided with the two property rights model.

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 priority 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 priority, $E(Q_l)$. The production possibility frontier is shown as the concave function. It is based on hydrological information, and reflects that reallocating water from lower priority to high security property rights requires additional period to period storage with associated losses of water to evaporation, seepage and in some cases extra overflow spillages during very wet periods. The frontier will have a slope$-\infty \leq \frac{dE(Q_l)}{dE(Q_h)} \leq -1$. Aside from these general properties, the particular position and shape of the production possibility frontier is dam specific and will depend on such factors as rainfall variability, temperatures and winds, and volume to surface area. 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 discussed above in the purchase and sale of water allocations attached to the two entitlements, and because of water user risk aversion. In the exceptional case of zero transaction costs, no risk aversion and an ability to store own water in the dam, the two entitlements could be regarded as perfect substitutes (per expected unit of water) with a slope

$$\frac{dE(Q_l)}{dE(Q_h)} = -1 \tag{8}$$

. Then, for the normal preference curves, the efficient mix of high security and lower priority water entitlements will be an internal one, at point E in Figure3, with the prices per unit of expected water per entitlement at the tangency point with $\frac{P_l}{P_h} < 1$.

With the passage of time, market circumstances inevitably will change, and they will alter the shape of the family of preference curves. But, in

most cases the direction of change, let alone the magnitude of change, will be uncertain. For example, in Figure 3 the indifference curve is shown as shifting from I to I' and becoming steeper. Reasons for an increase in the marginal rate of substitution between the high security and lower priority water entitlements include an increase in the product profitability of the relatively less water demand sensitive uses (eg households and perennial crops) relative to that of the demand flexible uses (eg annual crops), if risk aversion increased or the cost of some risk management strategies rose, or if transaction costs rose; and, vice versa for flatter indifference curves. A change in the preferences then would require a reallocation of the mix of water allocated to high security and lower priority water entitlements. In Figure 3, the shift in preferences from I with equilibrium at E, as shown in Figure 2, to the preference set with indifference curve I', requires a reallocation to F, and an increase in the relative price of high security water entitlement property rights.

To achieve the shift from E to F, or more generally any other change in the mix of high security and lower priority water entitlements, the water supply authority has an appropriate profit incentive. To illustrate for the shift from E to F, the water authority would purchase lower priority 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. Then, 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 priority entitlements in response to changes in market circumstances facing the different uses and users of water.

It should be noted however that the water authority would be a natural monopoly. 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 institutonal 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 pollution form, such as sewage and industrial waste disposal, and others are of the more difficult to measure non-point pollution form, such as chemical residues and downstream salinity from augmentation of the water table and from run-off water from irrigation. These pollution market failures provide a set of necessary, but not sufficient, conditions for government intervention to improve the efficient allocation of water. One policy strategy to internalise these externalities is to require water use licences, with the licence having regulations, taxes or required tradeable permits, as appropriate and specific to the different uses, regions and/or irrigation techniques (Young and McColl 2002). That is, conditions on water use licence may be employed as a targeted instrument for externalities. This approach permites the maintenance of a thick market for the trading of homogeneous water rights. The performance of the market might be enhanced by the creation of a range of derivatives.

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 the 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. In some cases, such as commercial fish and tourism, excludability is economically feasible, and market forces may be employed.

However, for the (probably more important) instances where public goods properties apply, the market fails,. In particular, unregulated markets will allocate too little water for environmental flows.

The set of necessary conditions for government intervention, and the general strategy of the policy intervention is discussed elsewhere (Freebairn 2003). For reasons of space and simplicity, it has been assumed in this paper that an appropriate allocation of water to the environment has been made, including the volume and timing of water flows. Attention in this paper has therefore been restricted to the allocation of remaining water among different extractive uses.

It would seem logical to extend the system of water rights for below-dam users to encompass above-dam users, such as those wishing to use water for forestry and farm dams. In an integrated system of rights, above-dam users would compete in the market for the same water rights as irrigators, households and industrial users below the dam.

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 2004).

7 Conclusions

In this paper, we have examined alternative options for defining property rights for water where aggregate availability 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-priority 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.

In addition to the water rights, a separate system of water use licences were proposed to allow for differences in water delivery costs and for any differences in external costs associated with particular uses of water. Government intervention was assumed to have taken a socially efficient allocation of water for environmental flows. Together, these assumptions mean that the analysis of the short term market for water allocations or temporary transfers, and the market for permanent transfers of entitlements or for property right stocks, has net demands (after delivery costs and any external costs) by households, industry and irrigation users (after an allocation for the environment). The water rights system is designed to give rise to a thick market for a physically homogeneous product (water at the dam wall), and to focus attention on the management of volatility in aggregate water availability.

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 allocation system of property rights requires more trading of temporary water than will the model based on high-security and lower-priority claims. Under a share allocation 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-priority claims, the high value and relatively inelastic demand users hold the high security water property rights which 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-priority 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-priority rights having strictly lower transactions costs than a share allocation system, even when the latter system is supplemented by a secure allocation.

The efficient mix of the high security water entitlement and the lower-priority 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 which alter the relative market prices of the water entitlements.

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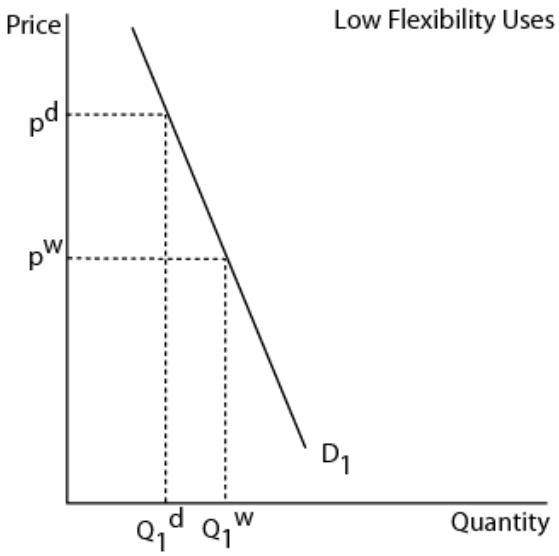
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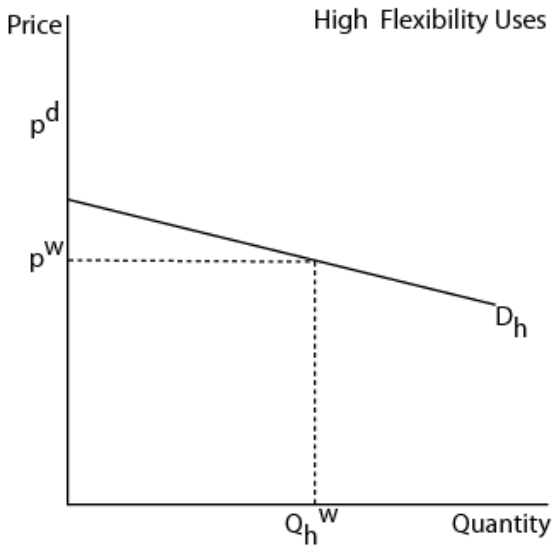
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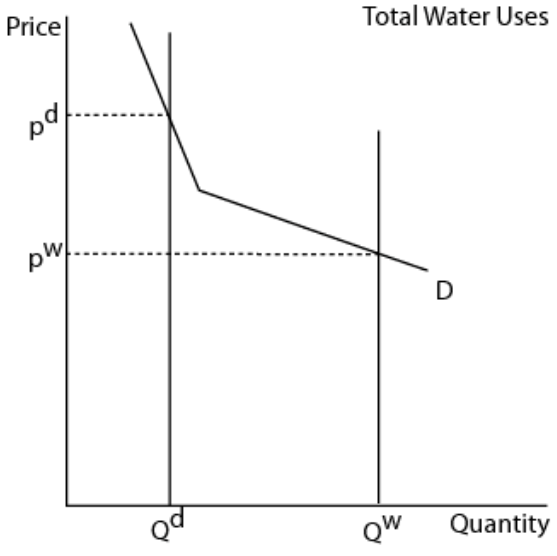
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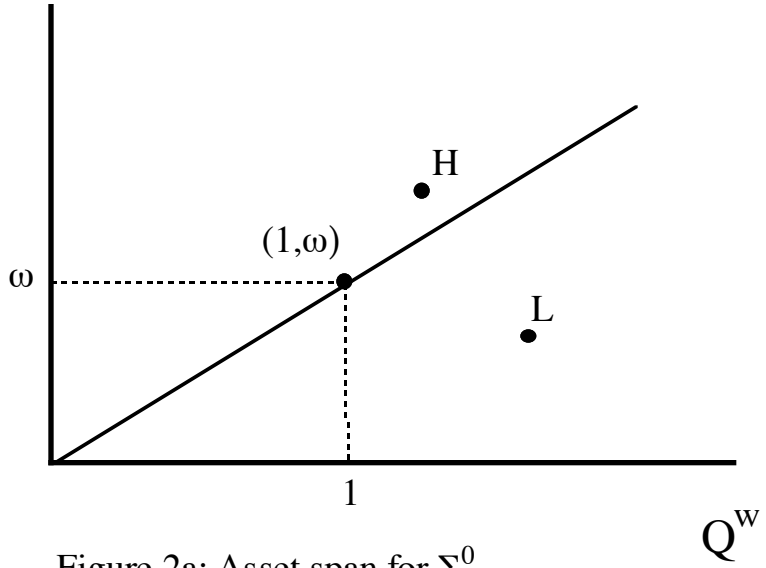

Figure 2a: Asset span for Σ^0

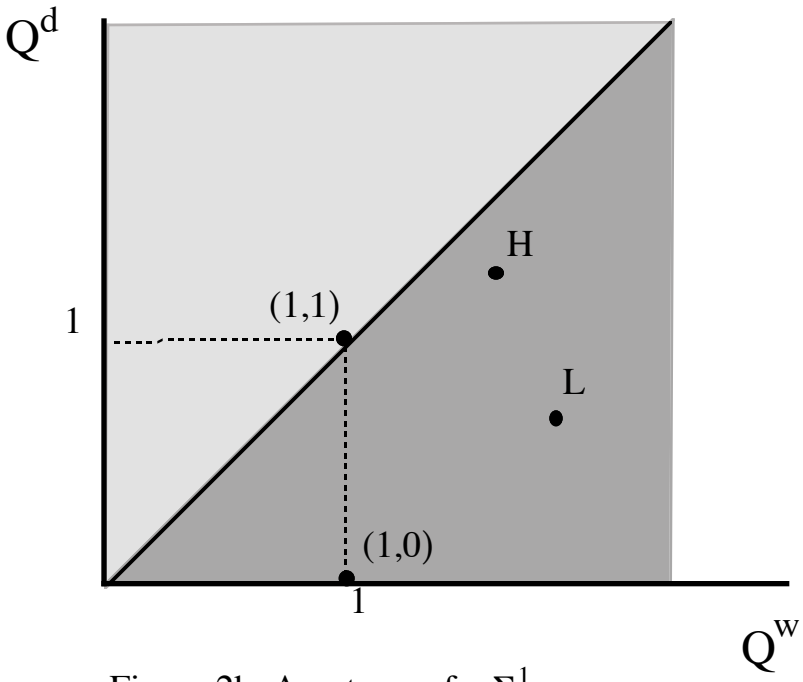

Figure 2b: Asset span for Σ^1

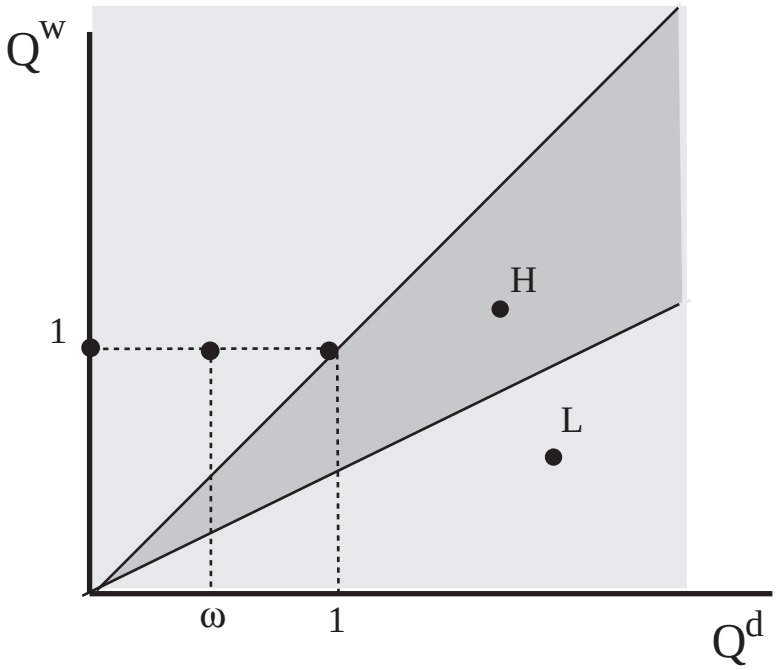

Figure 2c: Asset span for Σ^2

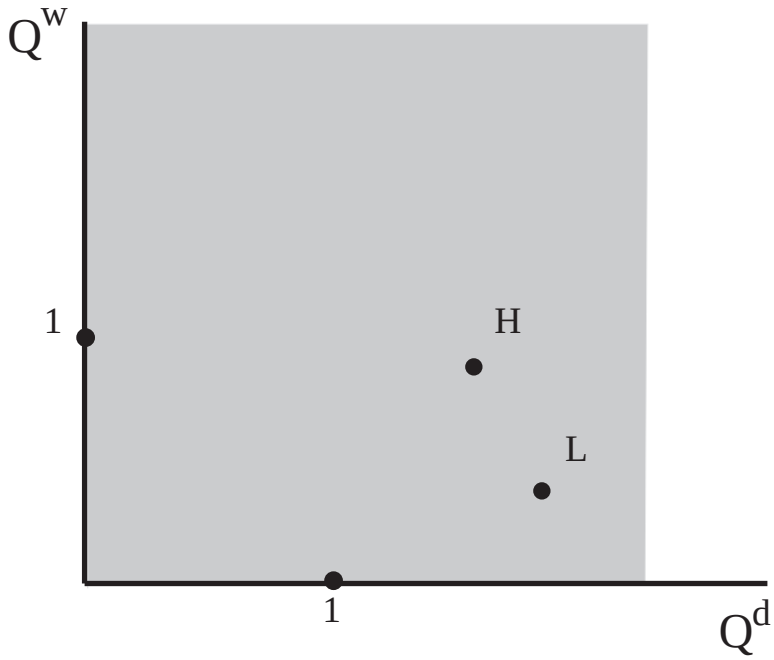

Figure 2d: Asset span for Σ^3

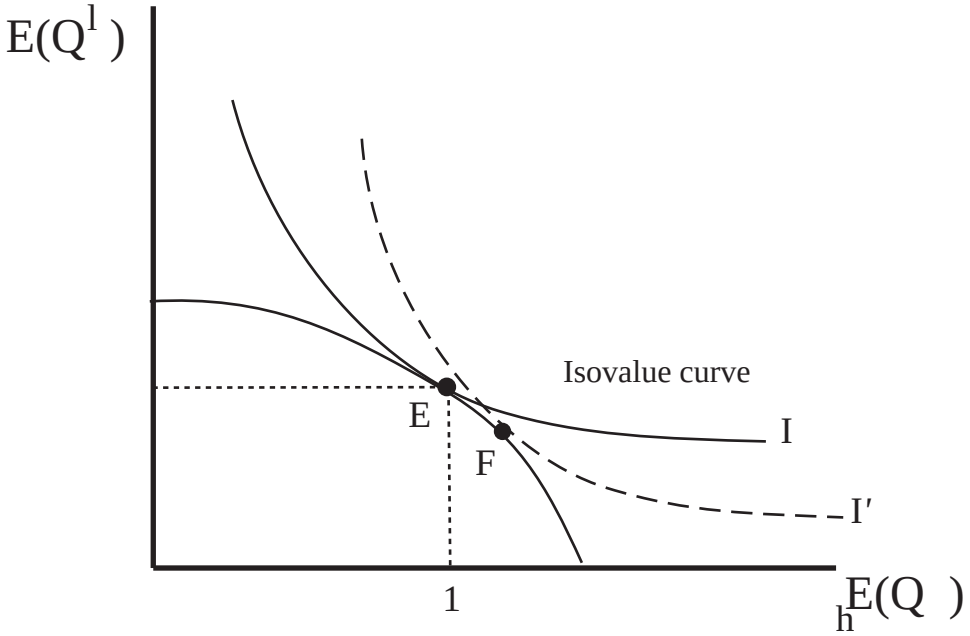

Figure 3: Efficient mix of entitlements