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TRANSFERABLE WATER ENTITLEMENTS WHICH SATISFY HETEROGENEOUS RISK PREFERENCES

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Irrigators in Victoria have a water entitlement which is composed of a highly secure water right and additional water which may be purchased if available. Water entitlements in NSW are based on the irrigated area with the actual volume of water received in any year depending almost entirely on seasonal conditions. Musgrave and Lesueur (1973) argued that these entitlements could be replaced by a portfolio of entitlements, with each type of entitlement in the portfolio guaranteeing a nominated minimum value of water at a different probability. Thus, irrigators could purchase a portfolio of water entitlements which would suit their individual risk preferences. The purpose in this paper is to show how a water authority can construct a portfolio of water entitlements which satisfies these requirements and also to demonstrate that the entitlements in the portfolio satisfy a first degree stochastic dominance relationship. A worked example is presented in which these results are illustrated.

Introduction

In the Eastern Australian States of Victoria and New South Wales (NSW), water entitlements from State irrigation schemes currently take the form of annual allocations which vary with seasonal conditions. Detailed discussions of the operation of these irrigated systems are found in DWR (1986, 1987), Alvarez *et al.* (1989), Turner and Weinmann (1989) and Uhlmann (1989). The institutional setting of the NSW and Victorian irrigation systems can be briefly described as follows.

In Victoria, irrigation farmers have a water right which is determined by that portion of their farm area which is suitable for irrigation. The water right varies with the irrigation district, the range being 1.02 megalitres per hectare (ML/ha) of suitable land for the Goulburn--Murray Irrigation District (GMID) to 9,144 ML/ha for the Merbein and Red Cliffs Irrigation Districts. In addition to this basic water right, additional water, called 'sales water' which is expressed as a percentage of the water right, is usually available. The volume of sales water depends on seasonal conditions. Irrigators pay a fixed charge for use of water up to their water right (whether the right is used or not) and are charged for sales water on the volume used in excess of the water right. Prices for sales water vary with the irrigation district and ranged

from \$11.88 per ML in the GMID to \$52.86 per ML in the Werribee Irrigation District in 1987/88. The water right is a very secure water entitlement. The Rural Water Commission operates its storages so as to guarantee that the water right can be supplied through a repeat of the worst recorded historical drought sequence. Over the past twenty years annual water allocations have ranged from around 200% of water right to 110% of water right, depending on the irrigation district and seasonal conditions.

The institutional arrangements for the management of irrigation water in NSW are quite different to those of Victoria. The standard water allocation in NSW is 6 ML/ha of irrigated land with the typical water licence being 972 ML. In 1987/88, NSW irrigators paid \$7.50/ML for water used in irrigation areas. Irrigation storages in NSW are not operated as carryover storages and hence water licences are less secure, with the security of supply varying markedly among river valleys. For example, irrigators in the Murrumbidgee Valley generally can plan on receiving at least half of their water allocations and having between 100% and 120% of allocations available on average, seven years in ten. Irrigators in the Gwyder Valley would typically have 100% of their allocations available on average only four or five years in ten with no irrigation water available in 5% of years. To compensate for this lack of security, the Department of Water Resources has recently allowed irrigators to carry over any unused allocation in its reservoirs, where storage losses would be lower than for on farm storage. It also permits irrigators to use water from the following season's allocation in the current season, subject to availability (which is generally very low).

Recently (1983/84 for NSW, 1987/88 for Victoria), irrigators have been permitted to trade their annual water allocations, and this allows irrigation water to be used where its short-run value is highest. Because the value of irrigation water during drought is high (due to low soil moisture levels and the limited availability of surface water), Musgrave and Lesueur (1973) argued that these types of entitlements should be replaced by tradeable, permanent water entitlements with different degrees of reliability. In this context, the reliability of water supply is defined as the probability that the volume supplied in a given period equals or exceeds the desired volume in that period (Loucks *et al.* 1981).

This is a sensible proposal because the economic consequences of water deficiency vary with the type of crop grown and with individual farm conditions and management. For example, water deficiency can permanently damage horticultural crops and perennial pasture but cause no permanent damage to annual pasture. In addition, the market price of transferable water under current arrangements can reasonably be expected to be high during drought, so that the purchase of high-reliability entitlements would act as insurance against paying high prices for additional water during drought. Under this proposal, ir-

rigators could purchase a portfolio of water entitlements with different degrees of reliability which would suit their individual preferences to risk, and which could be traded as required.

The aim of this article is to show how a State water authority could construct a portfolio of water entitlements, with each type of entitlement in the portfolio providing a nominated volume of water with a different degree of reliability.

In deriving the results of this analysis it is assumed that irrigation water is supplied from a single reservoir. This reservoir is operated using stationary reservoir operation rules which produce a stationary probability distribution of releases (or available water). Reservoirs supplying irrigation water in NSW and Victoria are currently operated using stationary operating rules. However, note that the stationary probability distribution of releases from a reservoir will generally depend on the operation rules employed (Hashimoto *et al.*, 1982). Furthermore, the reservoir operators attempt to find operating rules which provide a probability distribution of releases which meets their objectives.¹ The results of the analysis are obtained by assuming that stationary operating policies are being used. The issue of whether or not these policies are the best that can be found is not considered.

The remainder of the article is organised as follows. A basic statistical result, which is subsequently required, is derived in the second Section of the paper. In the third Section a method is presented of constructing a portfolio of irrigation water entitlements with each entitlement in the portfolio having a different degree of reliability. As well, there is a proof that an expected utility maximising irrigator would rank one unit of each type of entitlement in the same order as its degree of reliability. The fourth Section contains a proof that the entitlements in the portfolio satisfy a first degree stochastic dominance relationship. In the fifth Section a worked example is provided in which it is shown how the results of the article can be applied in practice. In the final Section a summary of the result is presented.

Statistical Results

In this section, a basic statistical result is derived which is required for the construction of a portfolio of water entitlements. The random variable X referred to below represents the total random release from a reservoir in a given irrigation season. The basic result involves partitioning X into k random variables, X_i , $i = 1, \dots, k$ which represent the water allocated to entitlement of type i in a portfolio of k entitlements, with each type of entitlement guaranteeing a specified minimum volume of water at a different degree of reliability. The statistical derivation is as follows.

¹ For an example of the derivation of reservoir operation rules which are required to meet specified release objectives, see Buras (1985).

Let X be a continuous random variable with a continuous probability density function (pdf) that is strictly positive on the open interval $(0, d)$, $d > 0$, and zero outside $[0, d]$. Under these assumptions, the cumulative distribution function (cdf) of X , $F(x) = Pr[X \leq x]$ is strictly increasing and continuous. The survivor function of X , $1 - F(x) = Pr[X \geq x]$ is therefore strictly decreasing and continuous on $[0, d]$, so that the survivor function of X has an inverse function which is denoted as $h(\cdot)$ ². Note that X can be partitioned into the k random variables

$X_i = p_i X$, $(0 \leq X_i \leq p_i d)$ with $0 < p_i < 1$, $\sum_{i=1}^k p_i = 1$ and that for specified constants: c_i , $(0 \leq c_i \leq p_i d)$, $i = 1, \dots, k$, the following probability statement holds:

$$(1) \quad \begin{aligned} q_i &= Pr(X_i \geq c_i) = Pr(p_i X \geq c_i) = Pr(X \geq c_i/p_i) \\ &= 1 - F(c_i/p_i), (i = 1, \dots, k) \end{aligned}$$

and using the inverse of the survivor function,

$$(2) \quad c_i = p_i h(q_i), (i = 1, \dots, k)$$

where (2) is a set of functional relationships for the variables c_i , p_i and q_i . This set of functional relationships satisfies the following additive property:

$$(3) \quad \sum_{i=1}^k c_i/h(q_i) = \sum_{i=1}^k p_i = 1.$$

It should be noted that results similar to (1), (2) and (3) apply if the range of X is $[e, d]$, $0 < e < d$ and the pdf of X has the properties outlined above on $[e, d]$.

In the context of water allocation problems, the subscript i refers to a demand type, k is the number of demand types, c_i the minimum volume of water required by demand type i , q_i is the reliability of c_i and p_i is the proportion of releases allocated to demand type i . For a geometrical interpretation of equations (2) and (3) and an application of these equations to evaluating the suitability of a reservoir operating policy, see Alaouze (1989). Buras (1985) has termed the inverse of the survivor function of reservoir yield, 'the reservoir yield function', and has graphed a tentative reservoir yield function for each of three seasons for the proposed Navagam Dam in India.

² The survivor function is used extensively in the statistical theory of reliability. For example, if X represents the time to failure of a machine component, then $1 - F(x)$ is the probability that a randomly selected component will have a useful life at least as large as x . Many applications of the survivor function to problems of component reliability may be found in Cox (1962). In the context of this section, $1 - F(x)$ is the probability that the reservoir will make a release at least as large as x .

The Construction of a Portfolio of Irrigation Water Entitlements

The purpose in this section is to show how the results of the previous section can be used to construct a portfolio of water entitlements, with each type of entitlement in the portfolio providing a nominated minimum volume of water of a different reliability. It will also be shown that an expected utility maximising irrigator would rank one unit of each type of entitlement in the same order as its degree of reliability.

As previously noted, it is assumed that irrigation water is supplied from a single reservoir which is operated using stationary operating rules, that the inverse of the survivor function of reservoir yield, $h(q)$, exists and that releases from the reservoir, X , lie in the range $e \leq X \leq d$, where $d > e > 0$, so that $h(1) = e$ and $h(0) = d$. It is also assumed that each type of entitlement in the portfolio is specified in terms of units of the minimum volume of water guaranteed by the entitlement at the degree of reliability specified for the entitlement.

Under these assumptions, equations (2) and (3) can be used to construct a portfolio of water entitlements with reliabilities in the range $0 \leq q_i \leq 1$, $i = 1, \dots, k$ where k is the number of different entitlements in the portfolio. These entitlements can have any two of the variables in (2), (p_i, c_i, q_i) specified, providing the resulting portfolio is feasible.

If c_i and q_i ($i = 1, \dots, k$) are specified, the proportion of releases allocated to entitlement of type i can be obtained from (2) and (3). However, the resultant portfolio may not be feasible because there is no guarantee that the resulting p_i , $i = 1, \dots, k$ will all be strictly positive. Therefore, for the purposes of illustration, the portfolio of water entitlements in this example will be constructed for specified values of q_i and p_i and equation (2) used to determine c_i , the minimum volume of water guaranteed with reliability q_i .

The portfolio of entitlements will be constructed with reliabilities spaced at equal intervals, i.e., $q_i = i/k$ ($i = 1, \dots, k$) and with equal shares of releases allocated to each type of entitlement in the portfolio, i.e., $p_i = 1/k$ ($i = 1, \dots, k$). Equation (2) can now be solved to determine the volume of water, c_i , guaranteed with reliability q_i for entitlement of type i in the portfolio:

$$(7) \quad c_i = p_i h(q_i) = h(i/k)/k \quad i = 1, \dots, k.$$

This portfolio of water entitlements has as elements the set of triplets (c_i, p_i, q_i) :

$$(8) \quad (h(i/k)/k, 1/k, i/k) \quad i = 1, \dots, k,$$

where $h(i/k)/k$ is the number of entitlements of type i in the portfolio. To ensure that there is at least one complete entitlement at each degree of reliability, the dimensions of reservoir releases, X , should be chosen so that $h(1)/k > 1$. This follows because the degree of reliability of an entitlement of type i is i/k which increases with i , reaching a maximum

of 1 when $i = k$. From (7), $c_i = h(i/k)/k$, and since $h(\cdot)$ is a strictly decreasing function, $c_k = h(1)/k$ is smaller than each of c_1, c_2, \dots, c_{k-1} . Requiring that $c_k = h(1)/k > l$ ensures that $c_i > l, i = 1, \dots, k$. Thus, each type of entitlement in the portfolio provides at least one unit of water at the nominated degree of reliability. The number of units of water guaranteed by each type of entitlement at the nominated degree of reliability can be made as large or small as desired by choosing an appropriate dimension for reservoir releases. This point is illustrated in the worked example of the following section 'A Worked Example'.

Consider any pair of entitlements: (c_l, p_l, q_l) and (c_m, p_m, q_m) with $m > l$. Since $m > l$ by assumption, $q_m = m/k > q_l = l/k$, and since $h(\cdot)$ is a strictly decreasing continuous function and $p_m = p_l = 1/k$, it follows from (7) that $c_l > c_m$.

One unit of each type of entitlement corresponds to the following shares of total releases: $1/kc_l$ and $1/kc_m$. From which it follows that:

$$(9) \quad X/kc_m > X/kc_l,$$

so that one unit of the entitlement with the higher reliability has a higher share of releases than one unit of any entitlement with a lower reliability.

Let $U(\cdot)$ be a strictly increasing, continuous utility function, and let $\Pi(\cdot)$ be a profit function which is strictly increasing in applied water over the range of water which one unit of each type of entitlement can potentially deliver. The profit function can be concave in water applied, however, it is assumed that the marginal product of applied water is not negative over the range described above.

From (9) the following inequality holds under these assumptions:

$$(10) \quad U(\Pi(X/kc_m)) > U(\Pi(X/kc_l)), \quad (m > l)$$

and taking expectations of both sides of (10) yields:

$$(11) \quad E[U(\Pi(X/kc_m))] > E[U(\Pi(X/kc_l))] \quad (m > l).$$

In equation (11) it is shown that any expected utility maximising irrigator would rank one unit of each type of entitlement in the same order as would ranking the entitlements on the basis of the size of their reliability. As noted above, this result indicates that the entitlements in the portfolio possess different risk characteristics and that irrigators with different attitudes to risk would purchase different combinations of entitlements from the State portfolio.

First Degree Stochastic Dominance in the Portfolio

If the functions $U(\cdot)$ and $\Pi(\cdot)$ possess strictly positive, continuous first derivatives, then a Theorem proved by Hadar and Russell (1969) indicates that the pdf of a single entitlement with degree of reliability m is at least as large as the pdf of a single entitlement with degree of reliability l in the sense of first degree stochastic dominance (FSD). In order to discuss this result and review the definition of FSD in the

context of the portfolio of water entitlements, it is necessary to obtain expressions for the cdf and pdf of a single entitlement with degree of reliability i .

Let Z_i denote the random variable representing the water delivered per season from one unit of the entitlement with reliability i , then the cdf of Z_i , $F_i(z_i)$ can be determined as follows:

$$(12) \quad F_i(z_i) = \Pr[Z_i \leq z_i] = \Pr[X/kc_i \leq z_i] = \Pr[X \leq z_i \cdot k \cdot c_i] = F(z_i \cdot k \cdot c_i)$$

and letting $f_i(z_i)$ be the pdf, of Z_i ,

$$(13) \quad f_i(z_i) = dF_i(z_i)/dz_i = f(z_i \cdot k \cdot c_i) \cdot k \cdot c_i,$$

where $f(\cdot)$ is the pdf of X .

The formal definition of first degree stochastic dominance can now be stated in terms of the pdf's and the cdf's of the random variables Z_l and Z_m :

Definition: The pdf f_m is said to be at least as large as the pdf f_l in the sense of first degree stochastic dominance if and only if:

$$(14) \quad F_m(z) \leq F_l(z) \quad \text{for all } z \text{ in } [a, b]$$

where $[a, b]$ is the closed interval where Z_l or Z_m are defined, i.e. $a = e/kc_l$ and $b = d/kc_m$.

In other words, this definition states that the probability that one entitlement with degree of reliability l delivers an amount of water in a season which is less or equal to z is at least as large as the probability that one entitlement with degree of reliability m will deliver an amount of water in a season which is less than or equal to z .

The theorem proved by Hadar and Russell (1969) can now be stated. *Theorem:* Let $H(\cdot)$ be a strictly increasing function with a continuous first derivative $H'(\cdot) > 0$ on $[a, b]$. Then:

$$(15) \quad F_m(z) \leq F_l(z) \quad \text{for all } z \text{ in } [a, b]$$

if and only if

$$(16) \quad E[H(Z_m)] > E[H(Z_l)].$$

The inequality in (16) is strict because Z_m and Z_l are different random variables. More general versions of this theorem have been proved by Hanoch and Haim (1969), Hadar and Russell (1971) and Teftatsion (1976). Hanoch and Haim (1969) define FSD in terms of (16) rather than (14).

Taking $H(\cdot) = U(\Pi(\cdot))$ with $U'(\cdot) > 0$ and continuous, and $\Pi'(\cdot) > 0$ and continuous on $[a, b]$, (10) is equivalent to (16), so that the Theorem of Hadar and Russell indicates that (15) holds for the entitlements in the portfolio. It is easy to verify directly (i.e. without referring to the Theorem) that (15) holds. Also, it not hard to show (by letting $a = e/kc_l$ and $b = d/kc_k$) that the entitlements in the portfolio satisfy the systematic FSD relationship:

$$(17) \quad F_k(z) \leq F_{k-1}(z) \leq \dots \leq F_1(z).$$

The interpretation of (17) is that the probability that one unit of an entitlement with a given degree of reliability delivers an amount of water less than or equal to z , is at least as large as the probability that one unit of an entitlement with a higher degree of reliability delivers an amount of water less than or equal to z .

Burness and Quirk (1979) obtain a result similar to (10) in their analysis of the appropriative doctrine of water rights which is used in the west of the United States. This doctrine bases the seniority system of water rights on the chronological order the right was obtained. The water allocation implication of this seniority system is that the holder of a water right may only extract an entitlement from the water source after the more senior right holders have extracted their entitlements. Under the assumption of a continuous, strictly increasing utility function and a profit function which is strictly increasing in water applied, Burness and Quirk show that water rights obtained under the prior appropriation doctrine can be ranked in the sense of first degree stochastic dominance, with a right of a certain seniority being strictly preferred to all rights with less seniority.

A Worked Example

The cdf of reservoir releases, $F(x)$, for a hypothetical reservoir is shown in Figure 1. In this section it will be shown how a portfolio of water entitlements for releases from this hypothetical reservoir can be constructed. The survivor function $q = 1 - F(x)$ and the inverse of the survivor function, $c = h(q)$ for releases from the hypothetical reservoir are shown in Figures 2 and 3 respectively.

A portfolio of water entitlements with degrees of reliability $q_1 = 0.25$, $q_2 = 0.5$, $q_3 = 0.75$ and $q_4 = 1.0$ will be constructed. In the notation of the section above ('The Construction of a Portfolio of Irrigation Water Entitlements'), $k = 4$. Equal proportions of releases are allocated to each type of entitlement so that $p_1 = p_2 = p_3 = p_4 = 0.25$. In order to use equation (7) to calculate the number of entitlements available at each degree of reliability, the following volumes are required: $h(.25)$, $h(.5)$, $h(.75)$ and $h(1)$ which can be obtained from the inverse of the survivor function (Figure 3). From Figure 3, $h(.25) = 5450$ ML, $h(.5) = 3950$ ML, $h(.75) = 2670$ ML and $h(1) = 500$ ML. Letting c_i denote the volume of water available at degree of reliability q_i for entitlement of type i , (7) can be used to calculate:

$$c_1 = 0.25 \times 5450 = 1362.5 \text{ ML}, c_2 = 0.25 \times 3850 = 987.5 \text{ ML}, \\ c_3 = 0.25 \times 2670 = 667.5 \text{ ML and } c_4 = 0.25 \times 500 = 125 \text{ ML}.$$

Thus, if the entitlements are denominated in one megalitre units, there are 1362.5 entitlements with degree of reliability 0.25, 987.5 entitlements with degree of reliability 0.5, 667.5 entitlements with degree of reliability 0.75 and 125 entitlements with degree of reliability 1.0.

FIGURE 1
CDF of Releases from a Hypothetical Reservoir

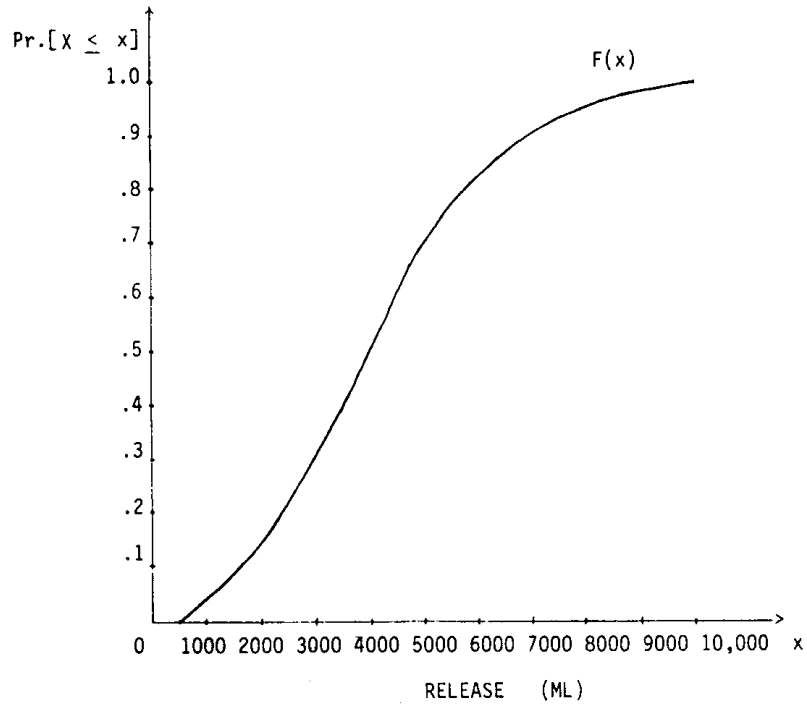


FIGURE 2
Survivor Function of Releases

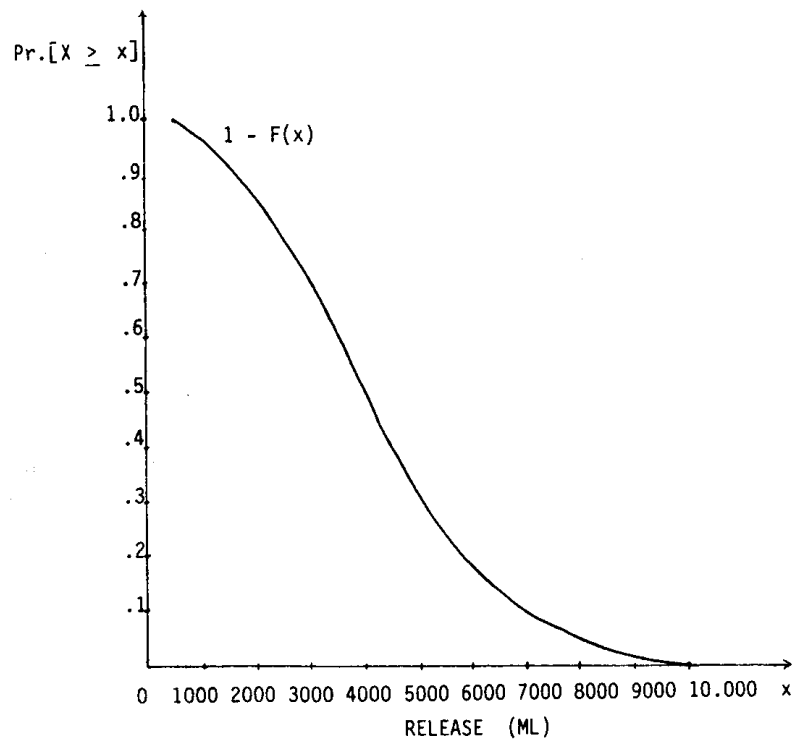
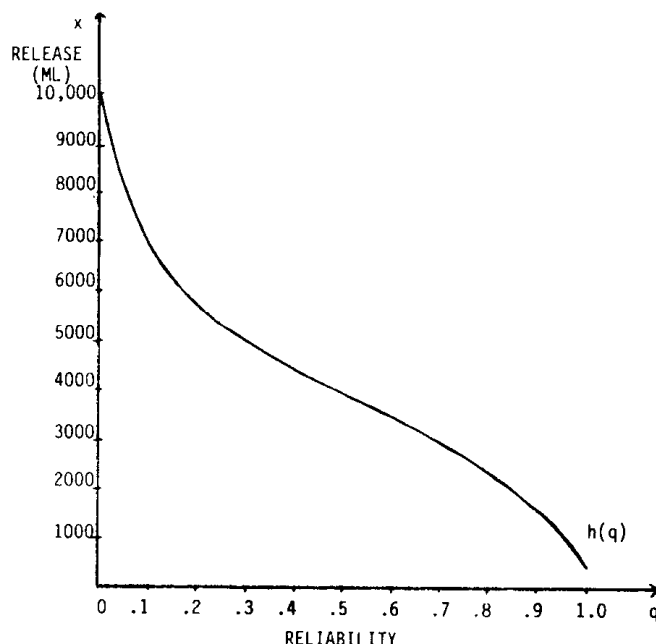


FIGURE 3
CDF of Releases from a Hypothetical Reservoir



To illustrate how these entitlements work in practice, suppose the reservoir operators intend to make a release in the current season of 5000 ML, then holding one unit of the entitlement with 0.25 degree of reliability provides an irrigator with $5000/(4 \times 1362.5) = 0.917$ ML of water, holding one unit of the entitlement with the 0.5 degree of reliability provides an irrigator with $5000/(4 \times 987.5) = 1.266$ ML of water; holding one unit of the entitlement with the 0.75 degree of reliability provides an irrigator with $5000/(4 \times 667.5) = 1.873$ ML of water; and holding one unit of the entitlement with the 1.0 degree of reliability provides an irrigator with $5000/(4 \times 125) = 10.0$ ML of water.

This shows that the volume of water received per unit of each type of entitlement increases with the degree of reliability of the entitlement. This is why an irrigator aiming to maximise expected utility with a profit function which is strictly increasing in the level of applied water over the range of water covered by one unit of each type of entitlement, would rank one unit of each type of entitlement in the same order as its degree of reliability.

Equation (12) will now be used to calculate the probability that delivered water to a holder of one unit of an entitlement with unit degree of reliability exceeds a given volume. Let Z_4 (ML) be the random variable denoting the water delivered to a holder of one unit of this type of entitlement. Since $Z_4 = X/(4 \times 125) = X/500$ and $500 \leq X \leq 10,000$, $1 \leq Z_4 \leq 20$ so that one unit of this entitlement provides at least 1 ML of water each season. The probability will now be

calculated that greater than 15 ML of water is delivered to the holder of one entitlement. For this example, $z_4 = 15$, $c_4 = 125$ and $k = 4$. Substituting these values into equation (12), it is found that $Pr[Z_4 \leq 15] = Pr[X \leq (15 \times 4 \times 125)] = Pr[X \leq 7500] = 0.94$ (from Figure 1). Thus $Pr[Z_4 \geq 15] = .06$ is the required probability.

Concluding Comment

It has been argued by Musgrave and Lesueur (1973) that the current tradeable annual water allocations made to irrigators in Victoria and NSW be replaced by permanent, tradeable water entitlements with different reliabilities. This would enable irrigators to purchase a portfolio of water entitlements which would suit their individual preferences to risk.

A method was developed in the analysis for constructing a portfolio of water entitlements, with each type of entitlement in the portfolio having a different degree of reliability. It was also shown that each type of entitlement in the portfolio satisfies a systematic first degree stochastic dominance relationship, which shows that an expected utility maximising irrigator would rank one unit of each entitlement in the portfolio in the same order as if the ranking were based on the degree of reliability attached to the entitlement.

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