Drought Water Rationing and Transferable Rations

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Abstract: Water rationing is a common, but little studied, technique for managing urban water supplies during drought. This paper reviews a wide range of approaches for implementing water rationing for urban drought management. These rationing approaches are assessed in terms of practical and theoretical performance. The paper then examines the potential benefits of allowing drought water rations to be transferable or marketable. Transferable rights have become a common suggestion for allocating scarce resources for a wide range of water-quantity and water-quality problems. Although attractive in terms of economic theories of resource allocation, transferable drought water rations often will be uneconomical for small transactions, due to likely high costs of completing transactions. However, transferable drought water rations might be useful for allocating scarce water among large industrial, commercial, and institutional users and among residential users with very different water demands. The equity effects of transferable drought rations would vary with the initial allocation of water rations. Legal aspects of how transferable rations might be implemented for public water-supply systems remain to be explored.

INTRODUCTION

Water rationing is a common demand-management approach during severe droughts. However, despite its prominent presence in many drought-management plans, its dire overtones, and its frequent use in recent Western droughts, water rationing has been studied little. This paper presents a wide variety of approaches for implementing water rationing for drought management. Theoretical and practical conclusions regarding these different approaches to drought management are also assembled.

To better develop and extend the theoretical aspects of drought water rationing, this paper proceeds to explore the potential desirability of "transferable" water rations for drought management in urban water systems. Transferable water rations are volumetric water rations granted to water-service customers, which would be tradable for cash to other water users. The intent of making water rations transferable would be to improve the economic efficiency of current water-rationing schemes, increase the flexibility of such schemes, reduce controversy concerning water rationing, increase consumer awareness of water use and its relative value, and generalize the motivation of water users to conserve water during drought.

Traditional water rationing during drought events restricts each household or enterprise to water use below a given level. Where households and other water users are heterogeneous in terms of how they value water use, such conservation measures can cause controversy between those with high water demands and those with low water demands. Such controversy detracts from the overall conservation intent of rationing programs. Moreover, simple rationing of a scarce resource is economically inefficient in that available water is not necessarily targeted for its highest and best economic uses.

Following reviews of water-rationing practice during drought and the application of transferable property rights to other problems, an economic approach to optimal ration-setting and transferable water rations is presented. Several methods for transferring or marketing drought water rations are identified and discussed. Illustrative examples are then presented, using the theory developed, to compare transferable drought water-rationing schemes with more conventional rationing schemes. Issues of equity and some practical matters also are discussed. Finally, some conclusions are presented. The intents of the paper are to review current rationing methods and lay the theoretical and conceptual groundwork for the possible use of "transferable" water rations.

WATER RATIONING IN DROUGHT MANAGEMENT

Water rationing has traditionally been a measure of last resort in urban drought management. In recent decades, water-conservation efforts have become common throughout the nation. Water-conservation efforts have been particularly intensive in the West, where drought-related water shortages often last for several years. Since the 1976–77 drought, California cities have undertaken particularly serious water-conservation efforts. With demands steadily rising and new supply development limited, water districts and water users have found that water conservation can be an inexpensive and effective means of saving water and delaying the need for additional water sources.

During the 1987–92 drought, many major cities in California quickly resorted to water rationing to limit water demand, and allocate limited water supplies between customers (Lund 1991; Lund et al. 1992). In California, water rationing has generally been found to be highly effective and not unpopular, relative to other alternatives (California 1991; Nelson 1979). Several forms of rationing have been practiced or proposed for drought water management (California 1991; Mercer and Morgan 1989). These are reviewed as follows.

Rationing by Fixed Allotment

Rationing by fixed allotment is the allocation of water by volume to each water customer. Each household is allocated a certain amount of water, as is each industrial, commercial, and institutional customer. In the case of household water rations, customer allocations might vary with number of persons per household or other characteristics indicating water needs. Allotments to industrial, commercial, or institutional customers might vary with the number of employees on site, historical usage, or other variables. Allotments might also vary seasonally.

Varying water rations by the characteristics of particular customers can reduce hardship for some customers and might equalize somewhat the water conservation inconvenience on all customers. However, such refinement of water rations imposes additional administrative, data-collection and -ma-

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nipulation, and enforcement costs on the utility. The development of water allocation formulas also necessarily creates some level of controversy and is inevitably imperfect. Some appeal and variance mechanism is also usually necessary.

Imperfections in fixed allotments arise when one customer gladly would pay, and another customer gladly would accept payment, for exchanging some amount of ration. Where water rations are uniform, or constant among members of a customer class, such willingness to trade requires that customers place different values on water use. Thus, a family placing more economic value on water use might be willing to trade some cash for water from another family, resulting in the same total water use but greater well-being to both parties to the transaction.

During the recent California drought, the East Bay Municipal Utility District (EBMUD) employed a generally uniform ration of about 400 gal/day (1.5 m^3/d) per household. The district is fairly hetergeneous, with many large, suburban customers on the hot and dry side of a range of high hills plus smaller, more urban customers on the more humid and cooler side of these hills (adjacent to San Francisco Bay). Average annual household water use on the humid side of the hills is about 236 gal/day (0.893 m^3/d), compared to 592 gal/day (2.24 m^3/d) on the arid eastern side (EBMUD 1991). The result was that the smaller customers on the humid side experienced less individual inconvenience from rationing than customers on the dry side of the hills.

Rationing by Percentage Reduction

Another common approach to water rationing is to create ration allocations as a percentage of use during some period prior to the drought rationing period. Such an approach might set a water ration to 75% of water use during a similar billing period in the previous year. Rations can be varied seasonally. During the recent California drought, many water utilities on the San Francisco peninsula chose this approach to rationing water.

This approach also poses some difficulties. First, it is sometimes difficult to establish water use during the predrought period. In a society where households often relocate, many residential customers will have no record of water use for the period prior to a drought. In some cases, the water use at the same address before the drought might be appropriate, but establishing the base for a percentage cutback remains problematic. A similar problem exists for new or newly expanded businesses. It is often not seen to be in the public interest to place water restrictions on a growing regional employer. As a result, some variance mechanism is also required with this approach.

A second problem with rationing by percentage reduction is its discouragement of long-term water conservation. If a business or household dutifully adopts long-term retrofitting to accomplish long-term water conservation, it can face less flexibility and disproportionate costs in responding to further water-use reductions during drought. From another perspective, a water utility with plans to implement this approach encourages customers to use more water in normal periods to assure a larger volumetric allocation in a shortage.

Rationing by Price

Higher water rates or prices typically have two roles during a drought. First, because often a majority of water district costs are fixed and less water is available for sale during a drought, higher rates often are required to maintain total revenues. Second, the higher water rates during drought are sometimes seen as having a role in reducing water demands (Moncur 1987, 1989).

The role of price in reducing water demand during drought is complex and somewhat controversial, due in part to the difficulty of separating effects of price signals from other factors that influence water demand. Direct and rapid price-stimulated reductions in water demand are often seen as being nearly negligible due to (1) the small income effect of water rates; (2) the relative price inelasticity of water; and (3) delays in customer implementation of water-conservation measures, particularly in the short term (Howe and Linaweaver 1967). However, under some circumstances, large price changes, severe shortage, public education, threats of rationing, and the public credibility of the water district can facilitate rapid response of water use to price changes (Hogarty and Mackay 1975).

Also, given the price inelasticity of demand for water, prices high enough to generate sufficient drought water conservation would often present water utilities with embarrassing financial surpluses during a drought. Still, a steeply increasing block rate for water is often used effectively to penalize use of water above a given ration amount. This approach is often used when the water utility feels it has insufficient statutory authority to directly ration a public service (California 1989, 1991).

Establishing a water-rate structure during a drought requires considerable judgment. A steeply increasing block rate can discourage, or penalize, excessive use without penalizing those customers that achieve required use reduction goals. However, it is uncertain how well customers will meet overall reduction goals. If a real crisis is perceived by customers, they are more likely to respond positively to requests for reduced water use (i.e., a large reduction in the demand curve). However, it the situation is not perceived as critical, getting an effective response from customers is often difficult.

Revenue requirements may also be uncertain due to unexpected expenses for conservation efforts or possible costs of emergency-supply augmentation. These added costs may be offset, however, by deferring planned capital expenditures for capacity expansion, maintenance, or other nonessential projects; maintaining a financial reserve for droughts or other emergencies; or by borrowing from an institution. The combination of increasing block-rate structure and uncertainty in customer water conservation response also make revenue forecasts during drought tenuous at best.

Weber (1989) has indicated that season, income, geographic location, temperature, and annual climatic conditions all have a greater influence on demand than price levels. Therefore, it would likely be impossible to adequately predict or control water usage using price alone. The distinction between price response and demand shift is important to consider, particularly given the large public education and other efforts during drought designed to shift the shape of customer demand curves. Assuming demand changes only in response to price is misleading.

Rationing by Restricting Specific Water Uses

During drought, water rationing is often accomplished in part with water-use restrictions prohibiting or restricting certain types of water use. The use of utility-provided water for car washing, sidewalk washing, fountains, and, in extreme cases, landscape watering may be limited. During the recent droughts in Seattle (1992) and Santa Barbara (1991), outdoor water use was prohibited for a time. Such restrictions essentially ration water by type of use.

The economic effect of this rationing approach is to neglect highly valued occurrences of a prohibited water use (such as washing a car before a wedding) without restricting low-value cases of unrestricted uses, such as leaking toilets or long showers. While such economic efficiencies are evident, this approach to rationing is easy to implement and enforce on a short-term basis. As such, this form of rationing might be especially useful for regions that tend to experience short droughts, where both rationing decisions and their implementation must be rapid.

Rationing by Service Outage

Many urban water supplies in less developed countries, lacking effective customer metering and other means of curtailing water consumption, ration water through rotation of service outage, allowing each sector of a city, say, only several hours of water service each day (Chau 1993). Although doubtless inconvenient and economically inefficient by almost any standard, and having public health risks, it is a practical approach for desperate and relatively uncontrolled conditions.

Accumulating Conservation Credits

Some rationing schemes can be made more flexible by allowing customers to receive credits for conservation beyond their ration. These accumulated credits would allow customers to use more than their ration later during the drought, up to the level of their ration plus accumulated credits. Such a rationing system with accumulation of credits was used in Marin County, California, during the 1977 drought (California 1979).

Allowing customers to accumulate and use credits for using less than the ration amount may have some advantages beyond customer convenience. Accumulating credits encourages additional water conservation. Indeed, if debits were prohibited, allowing credits should result in greater levels of conservation than rationing alone, at the same ration level. Risk-averse customers are likely to want some accumulation of credits for contingency use or to avoid penalties for accidentally exceeding the ration amount at some point.

Allowing customers to accumulate credits has special advantages for drought management in systems drawing from storage. For such systems, there is little risk that customers accumulating credits during the drought will cause a shortage by utilizing their credits all at once. Given storage, presumably there is additional stored water in the system resulting from the accumulation of credits by customers.

Credits would not work well in systems where droughts are very short. If droughts in a particular location last only a few weeks, there is little time for establishing and communicating a credit system with customers. There is also little incentive for customers to accumulate credits, because the drought will likely be over before the credits could be employed. This situation might be eased somewhat if consumers were paid for unused water-conservation credits at the end of a drought (Collinge 1992).

Allowing customers to use water beyond their ration early in the drought, creating water-use debits, would not seem wise. From an enforcement perspective, debits become awkward and distracting to administer and police. Also, from a water-conservation perspective, allowing debits would allow customers to avoid some water conservation entirely, because it would be difficult and largely pointless to enforce the debits once the drought had ended.

As urban water demands continue to grow and water supplies for urban use become more expensive and difficult to secure, it is likely that drought water rationing will become an increasingly common and controversial water-management decision. Fortunately, a wide variety of approaches are available for implementing drought water rationing. Unfortunately, there has been little systematic study and comparison of these approaches, particularly from a theoretical perspective.

If the use of water rationing is to become as sophisticated as many other water-utility operations, there is a need for serious behavioral studies of consumer response to and preferences for various forms of rationing, institutional studies establishing legal and administrative frameworks for implementing water-rationing schemes, and engineering studies to aid in the design of rationing programs and their integration with the great many other water-conservation and supply-augmentation measures available to water utilities.

The remainder of this paper suggests extending the range of water-rationing approaches available by allowing drought water rations to be transferable or marketable. In the examination of transferable water rations, economic theory is applied to drought water rationing in general, and further developed to study the potential of transferable drought water rations.

TRANSFERABLE WATER RATIONS

Fundamentally, transferable water rations involve the trading of rationed water supplies by customers within a single municipal and industrial water utility or district. This approach has parallels in other scarce-resource-allocation problems.

Other Examples of Transferable Rations

Transferable permits, rations, or other forms of resource allocations have been applied or discussed for a wide variety of resource-allocation problems. These applications include allocation of pollution loads among dischargers (Hahn and Hester 1989), development rights among property owners (Roddewig and Ingrham 1987), and access to congested transportation facilities.

Transferable water rights have long been advocated for allocation of water, particularly in regional and interagency settings (Milliman 1959, Howe et al. 1986). The transferability of rights to use water has long been of significant importance both between urban water agencies (Lund 1988) and between users within a single water agency, especially in the agricultural sector (Lund et al. 1992). It is common for large irrigation systems, both irrigation districts and especially mutual water companies, to allow and foster considerable trading of water between member water users (Enright 1989; Hartman and Seastone 1970). The transferability of water in such settings is often an essential feature of system operations, allowing the use of the system to vary with exogenous changes in market prices for agricultural products, agricultural yield, and water availability. The case examined in this paper is very similar to these long-standing transfers of water between agricultural water users during drought (Enright 1989, Maass and Anderson 1988).

Definition of Commodity Being Traded

In transferable water rations, the right to buy water from the water utility at a specified price is being transferred. Neither water in the physical sense, nor water rights in the traditional legal sense are transferred between parties to the transaction. Typically, during a drought, customers are allotted a rationed quantity of water at a normal or "base" price. Water use beyond the allotment is penalized through a significantly higher rate (excess use charge) or explicitly prohibited. The concept of transferable water rations is that a customer not using their full entitlement could sell the right to purchase their unused allotment at the base rate to another customer whose use exceeds their allotment. Collinge (1992) develops a similar approach for utility pricing in all years using a more ambitious system of transferable "discount coupons."

Water is not traded; rights to purchase water at a base rate are traded.

In some ways, municipal and industrial water-supply rations are well suited to transferability during drought. Each user's water use is typically measured and recorded accurately, ensuring that transfers of paper and real water are equivalent (Lund et al. 1992). In the semiarid western United States, droughts last for several months to several years and are foreseen by the end of the normal wet season, ensuring that there is opportunity for transfer transactions to take place. In regions with short droughts, the delays of arranging water-transfer transactions would tend to make transfers less useful.

Objectives for Transferable Drought Water Rations

It is difficult if not impossible to evaluate the value each customer places on its water. Although administrative allocations of limited drought water supplies may strive to be equitable and efficient, some group will always feel cheated and have cause to complain. Allowing transfers of water rations could alleviate some of the resentment from any initial allocation and lead to greater efficiency (in the economic sense), because customers with a higher value of water would be willing to purchase rations from those valuing water use less. Furthermore, a system of transferable rations would help to generalize conservation, because such efforts would result in creating a salable commodity. All customers would also have an incentive to be knowledgeable about their own water-use practices (Hayek 1945); this in itself could be beneficial in educating water users and leading to better water management. Therefore, water systems considering the potential application for transferable water rations might have the following objectives:

- Increase the level of consciousness among customers regarding water use and water as a valuable commodity.
- Generalize incentive to conserve water during drought water rationing.
- Increase economic efficiency and decrease the economic loss associated with a drought water shortage.
- Have greater equity and less controversy over the allocation of limited water supplies during a drought.

Institutional Mechanisms for Intrautility Water Trading

In agricultural water districts of the "mutual water company" type, intradistrict trading is commonplace (Enright 1989). For these mutual water districts, each member owns a share of the district's water rights, and mechanisms for trading or renting shares are established by the district or based on contracts between trading individuals. Urban water utilities have a somewhat different legal foundation. Most urban water utilities are legally established as a utility that must equitably serve demands within a service area, even in times of shortage, without regard for willingness to pay. This legal context would seem to hamper or prevent establishment of the necessary legal basis for transferable water rations during drought. Currently, little legal precedence is readily available to support intrautility transfers of water rations. Such legal support is likely to vary somewhat with local enabling legislation. However, several institutional mechanisms might be available to allow for transfers of water rations during drought.

Collinge's (1992) approach to rationing by issuance of tradable discount coupons for service seems a promising approach to providing equal service with tradable rations. Water use above that covered by coupons could occur, but only at a higher price to the customer. All customers would be provided with equitable service at the "discount" price by the initial allocation of ration credits. Water is not traded, only the right to purchase water at a base price is.

Another approach to facilitating water-ration transfers is to establish longer-term contracts with customers interested in participating in ration transfers during drought. These optional contracts would provide for alternative adminstration of service, including transfers of rations during drought. Such contracts would be similar to contracts for "interruptible" service, already common in electric and water utilities, in that it would be an optional arrangement between the customer and utility. By allowing customers to choose such an optional contract, customers would be self-selected, and would probably share the same aggregate shortage level within or outside the special transferable ration contract. Thus, the same aggregate service level would be maintained between the two groups. The long-term transferable ration contract also establishes transfer mechanisms before a drought occurs, a substantial logistical advantage.

For smaller-water-community water systems, it might be possible to subdivide water rights for the system, in a manner similar to the shareholder relationship of irrigators participating in agricultural mutual water districts. For arid regions prone to drought and with very heterogeneous water demands, changes in water utility enabling legislation might also be sought to allow more extensive use of transferable water rations.

Several other aspects of urban water customers are important to evaluate the potential for transferable drought rations. These include heterogeneity in customer willingness to pay for water and transaction costs incurred in the potential transfer of water rations.

WILLINGNESS TO PAY FOR WATER AND ITS HETEROGENEITY

Although detailed engineering economic studies are rare and often limited to local relevance, it is generally agreed that willingness to pay (WTP) to avoid water shortages varies greatly between water users and can vary to an especially large degree between water using sectors. This section reviews some relevant studies that hint at the range and shape of water-customer willingness-to-pay functions for avoidance of water shortage.

Residential Water Use

Residential water use has been found to be fairly heterogeneous based on household and neighborhood demographics and land use, socioeconomic status, lifestyle, and local microclimate (Howe and Linaweaver 1967; Weber 1989). All these sources of variation can be found in many water utility service areas, such as California's East Bay Municipal Utility District (EBMUD). The wide variety in households and their water-use patterns and purposes suggests a significant range of values that households place on water use. This is supported by studies in the income elasticity of water demand (Mercer and Morgan 1989; Boland et al. 1984).

Industrial Water Use

The heterogeneity of water value among industrial water customers is likely to be especially great. Industrial water users employ water for a wide variety of functions, using a wide variety of technologies, for the production of products with a wide range of market values. Thus, industrial values for water use are likely to depend on the particular design of an industrial facility, its operation, and market conditions for the enterprise's products.

A recent report (CUWA 1991) revealed a wide range of water values among different industrial enterprises in California. For industries selected from 16 three-digit Standard Industrial Classification (SIC) codes, self-reported income losses for small (0–15%) shortages were found to range from \$0 to \$518,000/acre-ft (\$420/m^3), averaging \$77,000/acre-ft (\$62/m^2). Larger shortages (15–30%) resulted in generally larger losses, from \$4,850 to \$643,000/acre-ft (\$4 to 521/m^3), with an average of \$143,000/acre-ft (\$116/m^3). Even if these self-reported estimates are high, it is evident that industrial-water-use values are both higher than normally expected for marginal residential and commercial uses as well as highly variable. The heterogeneity, variety, and idiosyncrasy of industrial values for water use are likely to make it difficult for water utilities to assess economically appropriate water rations. Transferable rations could greatly reduce this problem.

Commercial Water Use

There has been much less study of commercial water demand than of other major water-using sectors. Nevertheless, there is likely to be considerable heterogeneity in commercial water demand, given the wide range of types, uses, scales, technologies, and management forms characterizing commercial water users.

TRANSACTION COSTS

Involvement in market transactions incurs transaction costs. These costs include the costs to participants of gathering and considering information, making decisions, and paying any third-party expenses to undertake the transfer (such as brokerage costs). In the case of transferable drought water rations, both fixed and variable transaction costs could be expected. Fixed transaction costs would be incurred for any level of ration transaction, and variable transaction costs would vary with the amount of ration bought or sold. These costs are likely to vary with the type of user and the structure established for administering the transfer of rations.

For purposes of discussion, fixed transaction costs for households are likely to be on the order of \$10.00, based on an assumed 2 hr of time invested in making a transaction and a value of time averaging roughly \$5.00/hr. Institutional and industrial water users would probably invest more time in assessing and decision making for such transactions and with a higher hourly cost, perhaps averaging on the order of 25 hr of time investment at \$40/hr total cost, or a fixed transaction cost on the order of \$1,000. Commercial water users would probably have intermediate transaction costs in an urban water-ration market. The variable transaction costs would likely be the result of costs for administering the ration transaction process. Such a cost might be assessed per unit of water ration transferred. Indeed, the magnitude of such transaction costs are unknown, but seem likely to be of the order discussed and are likely to vary considerably both within and between customer sectors.

A wide variety of methods have been suggested for administering markets for transferable rights to scarce resources (Eheart and Joeres 1980; Eheart and Lyon 1983). These include a wide variety of auction, brokerage, and bipartisan transaction schemes. A promising approach for this particular case is the so-called smart market, in which a computerized algorithm is used to allocate a resource among buyers and sellers according to bids submitted by market participants (McCabe et al. 1991). Brokerage and smart-market approaches would likely reduce transaction costs, increase the speed with which transactions could be completed, and provide the required information and market forum needed to support many small transactions. Auctions might be more useful where the ration market included mostly large water users. Some ability to support bipartisan transactions would be desirable in any transferable rationing scheme to allow for more flexible reallocation of rations among users and as an alternative competitive forum to encourage efficiency in brokerage, auction, or other market forums. In this paper, the overall desirability of transferable rations is assessed with numerical examples, assuming bipartisan agreements between water users. Examination of bipartisan transactions was chosen because brokerages, auctions, and smart markets all require the economic feasibility of bipartisan transactions, and bipartisan transactions are easy to examine and explain.

OPTIMAL RATIONS AND ECONOMIC SURPLUS FROM TRANSFERS

This section develops the mathematics of least-cost rationing and the economic value of transfers of drought water rations. This mathematics supports two hypothetical, but not unrealistic, cases of water-ration transfers between residential water users and between industrial water users.

General Analytical Results

Some analytical examinations of rationing have been undertaken and reviewed by Tobin (1952) and Fakhraei et al. (1984). Their work is applied and extended to the particular case of transferable water rations.

Ideal Ration Quantities

Given loss or WTP functions $L_i(Q_i)$ for individual i reducing his or her water use by rate Q_i, the general condition for an ideal ration is given as follows, with the criterion of minimizing the sum of individual losses:

$$\min z_I = \sum_{i=1}^{n} L_i(Q_i) \tag{1}$$

subject to

$$\sum_{i=1}^{n} Q_i = s \tag{2}$$

where s = total shortage to be allocated, relative to expected normal demand. Where all loss functions are convex, the general solution conditions for this problem can be found by calculus

$$\frac{[\partial L_i(Q_i)/\partial Q_i]}{Q_i} = \frac{[\partial L_j(Q_j)/\partial Q_j]}{Q_j}, \quad \text{for any two water users } i \text{ and } j \tag{3}$$

$$\sum_{i=1}^{n} Q_i = s \tag{4}$$

This theoretically optimal solution is unlikely to be achieved in practice for a variety of technical, social, and political reasons. Generally, water utilities would be unable to estimate the required loss functions for a diverse customer base on a timely basis for drought water management.

Optimal Rations Following Transfers with Transaction Costs

To examine the optimal reallocation following transfer of drought rations, let Q_i = initial shortage allocated to each user i, and ΔQ_i = transfer amount desirable. The optimal set of transfers, including transaction costs, can be found by solving the following mathematical program:

$$\min z_T = \sum_{i=1}^{n} L_i(Q_i + \Delta Q_i) + T_v|\Delta Q_i| + T_f I_i \tag{5}$$

$$MI_i \geq |\Delta Q_i|, \forall i \quad (6)$$

$$I_i = \text{binary integer } [0, 1], \forall i \quad (7)$$

$$\sum_{i=1}^{n} \Delta Q_i = 0 \quad (8)$$

where M = a "large" constant; T_v = unit variable transaction costs of a ration transfer; T_f = fixed cost of participating in a ration transfer; and I_i = a binary integer variable indicating if user i has participated in a transaction. The objective is to minimize the sum of posttransfer losses plus fixed and variable transaction costs. Note that $z_f \leq z_T$, always, and that where T_v is "small," a user's involvement in transfers (incurring the fixed transaction cost T_f) will tend to result in shortage allocations equal to optimal ration allocations, $Q_i + \Delta Q_i + Q_i^*$.

Where the loss functions are convex, this problem can be solved using a binary-integer linear program. Were the solution to this mathematical program to be used as a basis for administering a smart market in water rations, the market-clearing price for rations would be given by the Lagrange multiplier (shadow price) for (8).

Analytical Results for Two Users with Quadratic Loss Functions

For generation of numerical results, the previous general formulations are simplified to the case of two water users, A and B, potential parties to a water-ration transfer. This bipartisan transaction forum is chosen to clearly illustrate the conditions of willingness-to-pay heterogeneity needed to support a market in drought water rations. Also, the theoretical feasibility of bipartisan transaction is required to support other forms of market forums, such as brokerages, where market price for rations would guide individual decisions.

In these examples, both users are assumed to have quadratic loss functions, $L_i(Q_i) = a_i + b_iQ_i + c_iQ_i^2$, equivalent to a linear demand curve for water. The analysis is illustrated graphically in Fig. 1. For this case, the ideal water ration needed to reduce total demand by s is

$$Q_A^* = \frac{2sc_b + b_b - b_a}{2(c_a + c_b)} \quad (9)$$

$$Q_B^* = s - Q_A^* \quad (10)$$

If actual rations have been allocated to create shortages to users Q_A and Q_B, respectively, then allocations after transfers of rations would be

$$Q_A' = \frac{2sc_b + b_b - b_a + 2T_v}{2(c_a + c_b)} \quad (11)$$

$$Q_B' = s - Q_A \quad (12)$$

However, if $L_A(Q_A) + L_B(Q_B) \leq L_A(Q_A') + L_B(Q_B') + 2T_v|Q_A - Q_A'| + 2T_f$, transfer of rations is uneconomical due to the friction of transaction costs, and the initial ration allocation will remain unchanged. This range of initial allocations under which transfers are economically desirable is illustrated in Fig. 1 by the darkened area. These analytical results are used to explore the potential utility of transferable drought water rations for two examples.

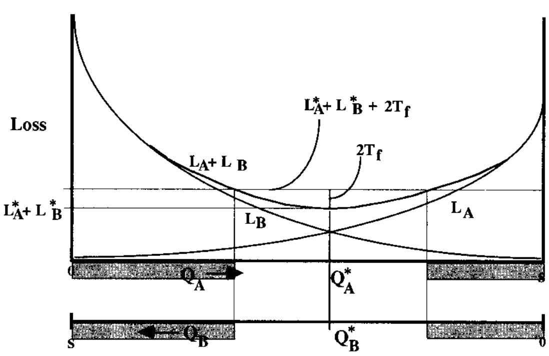

FIG. 1. Rationing Losses with and without Transfers for Two Water Users

TABLE 1. Example 1 Residential-Water-User Characteristics

Characteristic (1)	User A (2)	User B (3)
a	0	0
b	500	600
c	2,000	3,000
Normal water use (acre-ft/yr)	1	2
Normal water use (m³/yr)	1,233	2,466
Fixed transaction cost ($/transaction)	10.00	10.00
Variable transaction cost ($/acre-ft)	1.00	1.00
Variable transaction cost ($/m³)	0.0008	0.0008

Note: WTP = $a + bQ_i + cQ_i^2$, Q_i = shortage of i (English units).

Numerical Examples

The potential utility of transferable drought water rations is explored by examining two hypothetical cases, using what are probably reasonable loss functions and transaction costs.

TABLE 2. Example 1 Rations and Economic Performance

Ration (1)	User A (2)	User B (3)	Total (4)
(*a*) Ideal rations (minimizing total losses)			
Shortage Q_i (acre-ft)	0.61	0.39	1.00
Shortage Q_i (m³)	752	481	1,233
Shortage loss ($)	1,049	690	1,739
(*b*) Case 1a: Rationing by percentage of previous use			
Initial ration			
Shortage Q_i (acre-ft)	0.33	0.67	1.00
Shortage Q_i (m³)	407	826	1,233
Loss ($)	389	1,733	2,122
After transfer			
Shortage Q_i (acre-ft)	0.61	0.39	1.00
Shortage Q_i (m³)	752	481	1,233
Shortage loss ($)	1,049	691	—
Transaction costs ($)	—	—	20
Total losses and costs ($)	—	—	1,760
Gain from transfer	—	—	363
(*c*) Case 1b: Equal rations per household			
Initial ration			
Shortage Q_i (acre-ft)	0.00	1.00	1.00
Shortage Q_i (m³)	0.00	1,233	1,233
Loss ($)	0.00	3,600	3,600
After transfer			
Shortage Q_i (acre-ft)	0.61	0.39	1.00
Shortage Q_i (m³)	752	481	1,233
Shortage loss ($)	1,049	691	—
Transaction costs ($)	—	—	20
Total losses and costs ($)	—	—	1,760
Gain from transfer	—	—	1,839
Range of shortages not allowing transfers (acre-ft/yr)			
Minimum shortage	0.545	0.320	—
Maximum shortage	0.680	0.455	—
Range of shortages not allowing transfers (m³/yr)			
Minimum shortage	672	395	—
Maximum shortage	838	561	—

TABLE 3. Example 2 Industrial-Water-User Characteristics

Characteristic (1)	User A (2)	User B (3)
a	0	0
b	1,000	3,000
c	15	20
Normal water use (acre-ft/yr)	1,000	2,000
Normal water use (m^3/yr)	1,233,000	2,466,000
Fixed transaction cost ($/transaction)	1,000	1,000
Variable transaction cost ($/acre-ft)	1.00	1.00
Variable transaction cost ($/$m^3$)	0.0008	0.0008

Note: WTP $= a + bQ_i + cQ_i^2$, Q_i = shortage of i (English units).

TABLE 4. Example 2 Rations and Economic Performance

Ration (1)	User A (2)	User B (3)	Total (4)
(*a*) Ideal rations (minimizing total losses)			
Shortage Q_i (acre-ft)	600	400	1,000
Shortage Q_i (m^3)	739,800	493,200	1,233,000
Shortage loss ($)	6,000,000	4,400,000	10,400,000
(*b*) Rationing by percentage of previous use			
Initial ration			
Shortage Q_i (acre-ft)	333	667	1,000
Shortage Q_i (m^3)	411,000	822,000	1,233,000
Loss ($)	2,000,000	10,900,000	12,900,000
After transfer			
Shortage Q_i (acre-ft)	600	400	1,000
Shortage Q_i (m^3)	739,800	493,200	1,233,000
Shortage loss ($)	6,000,000	4,400,000	10,400,000
Transaction costs ($)	—	—	2,132
Total losses and costs ($)	—	—	10,400,000
Gain from transfer	—	—	2,498,000
Range of shortages not allowing transfers (acre-ft/yr)			
Minimum shortage	590	390	—
Maximum shortage	610	410	—
Range of shortages not allowing transfers (m^3/yr)			
Minimum shortage	727,470	480,870	—
Maximum shortage	752,130	505,530	—

The form of market (brokerage, bipartisan transaction, auction, etc.) might significantly affect the magnitude of transaction costs used in the numerical examples.

Example 1: Residential-to-Residential Transfers

The first example is of a hypothetical transfer of water rations between two single-family residential customers. Their characteristic normal water use and WTP to avoid shortages are summarized in Table 1. Both shortage avoidance WTP functions are assumed to be quadratic. In this case, each residential water user is somewhat different; the first uses a moderate amount of water annually with a moderate willingness to pay to avoid shortage. The second user has a much greater than average normal consumption and, perhaps due to affluence or a more water-intensive lifestyle, has a generally greater willingness to pay to avoid shortage. This range of normal water uses in not uncommon in many metropolitan areas. In California, variation in microclimate as well as income and lifestyle contribute to local variation in residential water use.

Two subcases are examined. In case 1a, the initial rationing scheme reduces each household's water use by one-third from normal water use; this is equivalent to a one-third overall reduction or a total reduction of one acre-ft/yr (1,233 m^3/yr) for the two households, with rations of 0.67 acre-ft/yr (826 m^3/yr) for user A and 1.33 acre-ft/yr (1,640 m^3/yr) for user B. In case 1b, equal water rations are given to each household [one acre-ft/yr (1,233 m^3/yr) for the coming year] to accommodate the same total shortage of one acre-ft/yr (1,233 m^3/yr). The shortages and economic performance of optimized (total cost minimizing) rationing, rationing by equal percentage reduction, and rationing by equal use are shown in Table 2.

For conditions represented by this example, ration transfers are very desirable for both common approaches to initial rationing. Ration transfers are particularly desirable where initial rations are fixed at a constant level per household. For this case (case 1b), user B would be willing to pay user A up to $2,909 (=3,600 − 691) to accept a shortage of 0.61 acre-ft (752 m^3) over the initial ration. Particularly for this second subcase, the ability to transfer rations results in significant improvements in economic efficiency as well as a transfer of income from user B to user A, presumably the less affluent water user.

In this example, the impact of transaction costs, while important, is not overwhelming. Only if initial rations for user A fall between 0.545 and 0.680 acre-ft (671 and 838 m^3) do transaction costs preclude the economy of ration transfers. Although transaction costs might pose a barrier to transfers in this example, transfer delays and transfer uncertainties (including lack of transfer information) might preclude the occurrence of ration transfers. For example, if the drought were short, on the order of weeks, there would be little time for residential water users to evaluate and arrange for the transfer of rations. Also, if the water utility does little to facilitate information and arrangements for ration transfers, there will be added delay and greater transfer risks and costs to parties pursuing ration transfers (Lund 1993).

Example 2: Industry-to-Industry Transfers

The great heterogeneity of industrial water uses and values of water use makes establishing water rations for industrial water users especially difficult (CUWA 1991). Tables 3 and 4 present the case of a hypothetical ration transaction between two industrial users, each of which has been allocated a shortage of one-third of normal water use. Table 3 lists the loss function, normal water usage, and transaction costs for the example. The economic loss function is taken to be that representative of short-term drought shortages, with magnitudes within reported ranges (CUWA 1991).

Table 4 contains the results of analysis of this problem, with ideal (minimum total loss) rations, losses from initial rations (one-third reduction from normal use), and losses and shortages after economically optimal transfer of rations. Total reduction in economic loss for this case is $2,490,000. The range of initial shortage allocations for which ration transfers are economically desirable is very broad. Industry-to-industry ration transfers are less likely to be hampered by information availability and transaction arrangement than residential ration transfers. Still, industry-to-industry ration transfers might prove impractical for short droughts unless prior arrangements are made. Such prior arrangements might be facilitated by utility drought planning that supports specific levels and types of drought rationing and provides information on likely frequencies (or recurrence intervals) for implementing various ration levels.

COMMENTARY

Drought water-ration transfers are most promising where a clear mismatch exists between the marginal costs of shortages experienced by customers under a given rationing scheme. Thus, if economically efficient rations are established initially, there is no incentive to trade rations. Given the practicalities of urban water rationing and concerns over fairness in allocating shortages, these mismatches are inevitable. The magnitude of mismatches is likely to be greatest where a water-use sector has great diversity and variability in water demand. Thus, ration mismatches are most likely to occur in the industrial sector, but also might be significant in commercial and some residential sectors.

Another important criterion in evaluating the potential of transferable water rations is the size of transaction costs. Transaction costs must be small relative to the overall shortage cost reductions possible from a water-ration transfer. For industrial water users, transaction costs might be quite large without negating the value of ration transfers. For residential water users, even small transaction costs will prevent many transfers (Reed 1990).

The equity and potential for wealth transfer of transferable drought water rations can also be important. Several approaches can be taken to evaluating the equity of alternatives. Here, we consider only the relative transfer of wealth (and increases in total wealth) resulting from different rationing schemes. The existence of transferable rations allows those selling rations to gain in monetary wealth from relatively less costly conservation, though this gain in monetary wealth will often come at an increase in conservation effort compared with nontransferable rationing schemes. Those purchasing rations lose monetarily through their purchase, but benefit from a net gain where their costs of additional conservation exceed the cost of purchasing rations. Thus, both parties increase their total wealth.

The initial allocation of rations in a transferable scheme thus poses an opportunity for real wealth transfer. By comparison, in nontradable ration schemes the equity in water wealth and shortage loss is all the equity consideration that is relevant. Without ration trading, no customer can gain absolutely from having been allocated more ration than the customer "needs." Because of this opportunity for some to reap real gains in wealth, equity issues associated with selecting initial rationing levels in a transferable scheme might be more controversial. Water utilities often seek to avoid such controversies. However, in this case, such avoidance of controversy can result in real economic losses.

Permitting transfer of drought rations might have practical advantages as well. The ability to transfer rations should reduce the need for rationing variances and administrative proceedings, although it will probably increase the need for public education efforts and establishing a forum for arranging and recording ration transfers.

Although transferable drought water rations appear to offer several theoretical and practical advantages over conventional water-rationing schemes, several aspects of their implementation remain to be examined in practical detail. Legally, the administrative and water-rights authority of water utilities to create an internal water market remains to be established, and is a practical prerequisite for establishing a transferable water-ration system. Economically (and perhaps sociologically), there is little understanding as to how to best develop a forum or forums for facilitating market transfer of water rations with low transaction costs and price setting at marginal costs. And politically, it remains to be seen if such an approach to drought rationing would find sufficient support among the competing interests involved in the governance of urban water utilities.

CONCLUSIONS

Although rationing is never nice, it is sometimes necessary. Fortunately, many forms of water rationing are available for urban drought management, each with different advantages and disadvantages under different circumstances. Nevertheless, there is little systematic research on the application and integration of water rationing into urban water systems. The economic costs and inconvenience of rationing also provide incentive to explore approaches to improve water rationing. This paper has examined the desirability of transferable or tradable drought water rations for drought management.

The potential usefulness of transferable drought water rations requires heterogeneity in the losses of different users due to water shortage and/or economic inefficiency in the initial allocation of drought water rations. Given the diversity of urban water users and the difficulty of establishing economically efficient allocations of shortage during drought, these conditions are probably present in most major urban droughts.

The examples presented here indicate that transferable water rations would be economical for a number of industrial and some residential water-rationing situations, although industrial-sector applications seem most promising. An additional practical concern for drought water rations is that the droughts endure long enough for individual water users to make decisions and arrangements regarding ration transfers. Especially for residential users, this requisite drought length is unlikely to be present in humid regions, where droughts may span only a few weeks or months.

Transferable drought water rations appear to be most promising for industrial-sector water users, where water values are the greatest, most heterogeneous, and difficult to assess by a water utility. The selection of a market forum (brokerage, smart markets, auction, etc.) will affect the costs and delays of ration transactions, perhaps spreading the applicability of transferable rations to a greater proportion of water users and shorter drought events.

In all rationing schemes, equity issues are prominent and controversial because drought management often rests on creating a public image of shared sacrifice. The use of transferable water rations would likely increase such concerns, because such a system implies the possibility of some users selling enough water rations to achieve a net increase in wealth after conservation. Thus, the initial allocation of rations is especially important for transferable rationing schemes and a potentially serious source of controversy for their implementation. The legal basis for intrautility water transfers also remains to be established.

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