MINING OF AQUIFERS NEAR METROPOLITAN AREAS: TOWARDS A GENERAL FRAMEWORK FOR POLICY ANALYSIS

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ABSTRACT

In addressing the question of optimal, inter-temporal extraction policy for a near-urban aquifer, specification of an economic objective function requires decisions about benefit estimation, the relevance of alternative supply sources, linkages with urban planning or regional economic development policies, and the importance of environmental externalities such as the depletion of wetlands or land subsidence. Four stages of aquifer development are highlighted, namely those of (i) initial development, (ii) wetlands impact, (iii) depletion, with or without land subsidence, and (iv) exhaustion. Economic decisions in each stage are then discussed in terms of models drawn from the literature. The models are illustrated using examples from Perth (Western Australia), Tucson (Arizona) and Bangkok (Thailand).

1 INTRODUCTION

The literature on economics of groundwater extraction is dominated by examples based on agricultural use of a single aquifer. The basic tradition began with a series of papers by Burt (1964a, 1964b, 1966, 1967) in which decision rules were derived for inter-temporal allocation. Groundwater stocks were treated as being partially renewable by a stochastic process, and benefits of extraction were imputed by reference to the value of water as an intermediate input to an irrigated cropping industry composed of multi-product firms. Under Burt's decision rule an optimal policy would be to mine groundwater stocks at a gradually decreasing rate so that the long- run equilibrium withdrawal rate converges on the rate of recharge. Brederhoeft and Young (1970) examined the implications of spatially-variable withdrawals, incorporating a rather complex hydrological model, and concluded that postponement of current withdrawals in favour of future needs coupled with management through positioning of withdrawals could improve the economic yield from irrigated agriculture, but also deduced that it would sometimes be optimal to exhaust or abandon an aquifer. In these cases farmers would simply shift to dryland farming, or quit farming in the area if the water table were to fall below its economic threshold.

Groundwater extraction near metropolitan areas raises issues which require more than simple extension of such agricultural models. In this paper we argue that growth in willingness to pay for water in a metropolitan area may easily outstrip growth in the direct costs of groundwater extraction in the short term. This can lead to a major adjustment problem in the long term. Thus, taking account of long-term adjustment costs and shifting demand becomes essential for determining an optimal trajectory. In these circumstances the informational role of efficient pricing policies for water users and managers is often underutilised. Also, in urban contexts, external effects of groundwater extraction, which have not generally figured in agricultural analyses, may have significant, discrete impacts; for example through depletion of wetlands or serious land subsidence. Finally, for an urban area the decision to proceed with aquifer mining will need to be taken in the context of the array of alternative sources. These differences affect the form of economic objective function to be maximised, the range of alternative plans to be considered, and the policies which may be implemented. In the following section a simple model of aquifer development is presented as a basis for discussion of policy models.

2 A GENERAL MODEL

2.1 The groundwater system

Assume a single, unconfined aquifer with defined lateral bounds and base. In its undeveloped state net lateral boundary flows are equal to positive and unvarying net recharge, while at the base there is zero vertical flow. Thus, in the undeveloped state there is a stable hydrological equilibrium that leaves depth to water table constant. Wetlands may occur where the constant water table intersects the ground surface, or the phreatophytic zone. Development of the aquifer entails change in the water balance equation, but at any groundwater depth the system may be balanced, with total inflow equal to total outflow. Thus there is some quantity of water (W) that may be pumped per unit time, at any groundwater table depth, that maintains that depth. Associated quantities of withdrawn water and stable groundwater depths may be graphed as SS' in Figure 1. These depths and their associated quantities may be discussed as four "Stages" of development.

In Stage I the groundwater table falls only slowly in response to increasing withdrawal, as recharge responds positively to declining water table level through a reduction in evapotranspiration losses. Other hydrological influences in this initial Stage may be recharge enhancement from urban development above the aquifer, and acceleration of flows towards wells, which have the same effect on the withdrawal/water table relationship. For ease of exposition we assume that the effects of drawdown on wetlands are negligible in Stage I.

In Stage II greater withdrawal per unit time results in an increasing rate of decline in the groundwater table. But stability is still attainable by increasing the rate of withdrawal and then waiting for the groundwater table to stabilise at a new, lower level. Conversely, the water table can be raised to a new, stable level by a permanent reduction in the rate of withdrawal. The upper limit of Stage II is at the maximum withdrawal rate that is consistent with a stable water table: this is conventionally termed the maximum sustainable yield (MSY), and is equal to net available recharge. Any wetland must by definition be eliminated by the end of Stage II, since wetlands are a major source of evaporation losses.

Stage III covers the range of water table depths from the end of Stage II to a point below which the aquifer cannot sustain withdrawal. For water table stability, withdrawal must equal net available recharge: but the management policy may be to mine the aquifer, by setting withdrawals in excess of MSY, and allowing depth to decline. Stability may then be recovered by subsequently reducing the withdrawal rate. Ultimately, it is inevitable that the withdrawal rate must fall back at least to the MSY. If it is brought to below the MSY the water table will begin to rise once more.

Stage IV has been reserved for the narrowing aquifer lying at the bottom of the system. Entry into this Stage may lead to the economic failure of the aquifer, in which case withdrawals must go to zero. Alternatively, entry into Stage IV may be conceived as being reversible by a reduction of withdrawals.

2.2 Demand-supply relationships

The upper portion of Figure 1 shows water demand curves, DD', superimposed on a backward-bending marginal cost curve for water production, CC', that corresponds to the set of stable aquifer states SS'. The presentation closely follows the model of fisheries management (see, for example, Butlin, 1975).

Cost is lowest in Stage I, as here the aquifer is most easily accessible. Marginal cost initially falls in Stage I as economies of scale are realised, but eventually this effect will be counterbalanced by increasing cost as a function of depth to water table, through Stages II and III. The marginal cost locus in Stage IV depends on the withdrawal trajectory, and in particular whether mining proceeds to the point of exhaustion. Certainly, costs would be expected to rise sharply if pumping efficiency declined rapidly. Note that CC' is the locus of marginal costs for stable aquifer states. The withdrawal rate could exceed MSY with relatively low marginal cost, at least in the short term, but mining would eventually cause marginal costs to return to a point on CC' corresponding to the the particular stable state reached. The dashed lines in Fig. 1 show one, possible non-stable trajectory.

Demand for water, DD' and DD*, expressed as a function of price and assumed to be independent of production cost, is influenced by population, incomes, technology, consumer tastes, conservation practises and so forth. It follows that the combination of static economic equilibrium (intersection of demand and marginal cost curves) with stable physical equilibrium (between water withdrawal and groundwater depth), can only be achieved by chance or through calculated social choice. The effect of regional economic growth will be to shift the demand curve rightwards, and overall stability may then only be attained by price changes or measures acting directly on the demand curve.

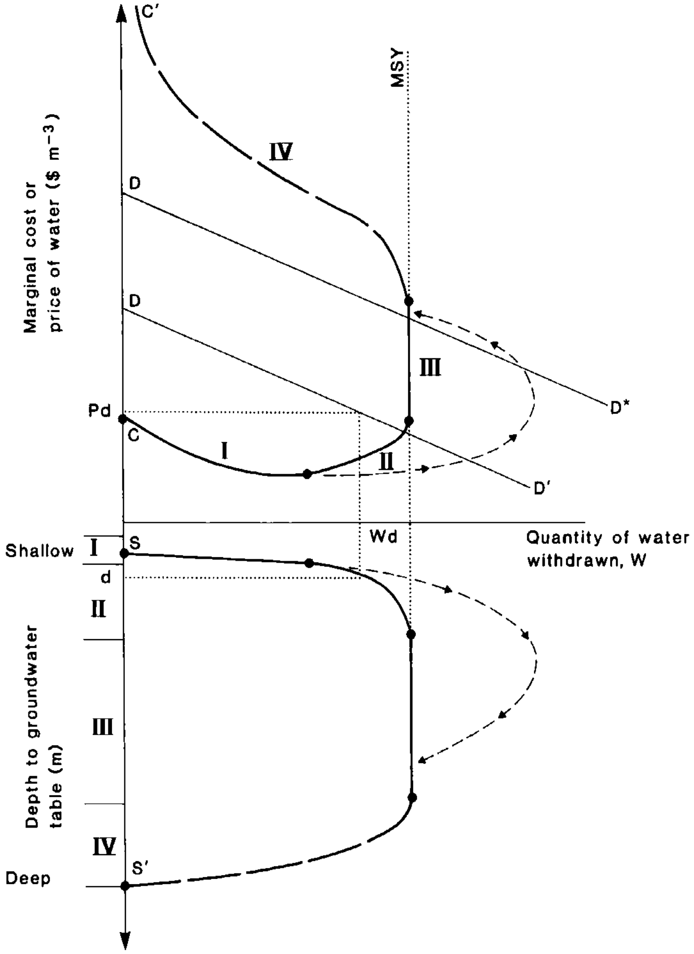

Fig. 1. Demand and marginal cost curves related to the locus of stable states for an aquifer, illustrating a non-stable trajectory of withdrawals.

3 ECONOMIC DECISIONS

3.1 A basic social benefit function

The basic criterion for an economically efficient trajectory of aquifer states is taken to be the same for all stages: namely that the trajectory should be such as to maximise the the discounted sum of consumer and producer surpluses. We write this basic social benefit function as:

$$Zk = \underset{Wk}{\mathrm{Max}} \int_{t=0}^{\infty} e^{-rt} B(Wk(t),t) - C(Wk(t),t)\, dt\ , \tag{1}$$

where $B(Wk(t),t)$ is the flow of benefits from $W(t)$ units of withdrawn water at time t from aquifer k; $C(Wk(t),t)$ is the corresponding flow of costs; and r is the social rate of discount. However, as we demonstrate, the plans and policies available to decision makers, and their hydrological and economic implications, will differ between Stages, and so the precise formulation of this basic economic criterion will also differ.

3.2 Stage I

If a competitive market for water exists, the marginal cost and demand curves must intersect in the range $0 < Wk(t) \leq W1$ (Figure 1). As any more efficient source of water will have already been developed, and as (by assumption) there are no environmental effects, it is not necessary to consider any alternative source for the urban area, except in the unlikely event that marginal cost rises above that of an alternative source while the aquifer is still in Stage I. Benefits and costs of extraction are, strictly, temporally interdependent, because of the postulated fall in depth; but the effect is likely to be trivial in practise, and may be negligible if, for example, urbanisation is increasing recharge to the aquifer.

3.3 Stage II: Wetlands depletion in Perth, Australia

With the begining of Stage II both the future state of the aquifer and the possibility of utilising alternative sources enter into the problem of choosing the state trajectory. The future state becomes important because increasing the rate of withdrawal increases future extraction costs. Increasing the rate will remain economically optimal as long as willingness to pay in a given year exceeds the marginal cost of production plus the sum of discounted sum of extra unit cost for the original quantity of water over all future years. The policy for public policy is taking account of all future costs. Most obvious is the elimination of wetlands and their associated flora and fauna. This may be a cost or a benefit, depending on the circumstances, but is unlikely to be reversible. In the absence of alternative sources, a simple expansion of the social benefit function as follows would reflect the problem:

$$Zk = \underset{Wk}{\mathrm{Max}} \int_{t=0}^{\infty} e^{-rt} \; B(Pk(t),t) + B(Wk(t),t) - C(Wk(t),t) \; dt \qquad (2)$$

where B(Pk(t),t) is the flow of net social benefits from P units of preserved wetlands above aquifer k at time t, and other terms are as defined. (A problem here is that due to scale economies a non-convex optimisation is required.) The rate of withdrawal should never exceed Wd (Figure 1), the maximum consistent with wetlands preservation, provided that the loss of discounted benefits from wetlands plus the discounted direct costs of aquifer use were greater than the discounted direct benefits of aquifer development.

A major problem, however, is that maximisation over the domain of the particular aquifer is unlikely to yield a social optimum if alternative sources are available. In that event the single-aquifer result will appear as a strictly local optimum, and irrelevant to policy makers. If an environmentally-neutral alternative source exists, the relevant social benefit function is:

$$Zj,k = \underset{Wj,k}{\mathrm{Max}} \int_{t=0}^{\infty} e^{-rt} \; B(Pj(t),t)+B(Wk(t),t)-B(Wj(t),t)-C(Wk(t),t)+C(Wj(t),t) \qquad (3)$$

in which B(Pj(t),t) is the flow of benefits from wetlands preservation in source j, and the other terms define direct benefits and costs for the two sources. Thus the benefits from development of the particular aquifer are now calculated as the advantage in net benefits over the alternative source. If it is assumed that the two sources would be developed at the same rate over the whole planning period, the positive and negative direct benefit terms in (3) sum to zero. The social benefit function then closely resembles that of Krutilla and Fisher (1975).

Perth provides an example of a Stage II aquifer. The metropolis, with a population of around one million, is situated on a sandy coastal plain which is underlain by unconfined aquifers. The water table intersects the ground surface in inter- dunal depressions, forming lakes and wetlands which are of recreational, visual, and biological significance. Groundwater is extracted for both public supply (up to 40% of metropolitan public supply), and by private users for irrigation of crops, open spaces and residential gardens. Even though rights to groundwater are vested in the State Government, private access was loosely controlled in the past. This has led to difficult problems of allocation now that public and private uses have taken the aquifer into Stage II, and some wetlands are threatened. Allocation of privately-extracted groundwater is by licence and quota for commercial users, and by licence for residential users (without volumetric quota). There is a multi-block tariff for residential users of public supplies, but not in the commercial sector. Extraction policy is being set by reference to the water table depth required to maintain wetlands, and is lower than the MSY. Research into the recharge characteristics of alternative land uses, including urban development, native heathland vegetation, and pine plantations at various densities is aimed at modifying the water balance of the aquifer by land use change on government-controlled land. This will change the position of the SS' curve, possibly allowing greater withdrawal while maintaining the wetlands.

Several prerequisites for development of an economically efficient policy can be highlighted. First, whereas Stage II evaluation should ideally be based on a two-good, two-source model, all analyses so far have been based on single-aquifer simulations. Nearly all the potential water sources that have low direct costs would also have environmental impacts if developed, and the W.A.Water Authority is obliged by law to select sources according to direct cost effectiveness. Second, if, as is planned, the population and economy of the Perth region continue to grow, the positive difference between the marginal value and the marginal production cost of groundwater will increase. Achievement of both equilibrium in water markets and environmental objectives requires either a groundwater pricing policy or a quota system that reflects the true opportunity costs of groundwater mining. Cross-price elasticity of demand for privately-extracted groundwater with respect to public water supply price also needs to be taken into account in public supply pricing (Thomas and Syme, 1987). Third, the rents from the holding of water entitlements will continue to grow, and the potential payoffs from lobbying and litigation will increase. A change of rationale in water pricing from being direct-cost based to resource-rental based would be one way of extracting rents from the system. Finally, the model discussed provides an economic framework for assessing the benefits of recharge manipulation.

3.4 Stage III: Single source, without environmental effects: the case of Tucson, USA

Once an aquifer is in the third Stage of development it may be viewed as a declining, if partially renewing, stock resource. The problem becomes that of inter-temporal rationing of a limited, exhaustible resource, taking account of the economic welfare of water users via the cost and quantity of water available to them. This is the stage in which Brederhoeft and Young would first mine water, then decrease the withdrawal rate over time. The B-Y formulation can be shown as a special case of the general model. However a major difference for an urban area is that shifts in demand rather than inter-temporal changes in water extraction cost are likely to dominate the result.

Following the model in Figure 1, a B-Y type formulation would require accurate forecasting of demand and long-term costs of adjustment to supply failure, within the single aquifer model. However, it can be shown that little reliance needs to be placed on either long-term forecasting of demand or of future aquifer states and associated costs, if the problem is considered in terms of asset equilibrium theory, rather than in terms of the resource flow alone (Dasgupta and Heal, 1979). The owner/manager of an exhaustible resource, who also owns other kinds of asset (termed numeraire assets), faces the choice whether (i) to keep the numeraire asset stock at its current level, or (ii) sell the asset and buy one unit of water right which can be sold at a later date at an increased price. Within Stage III, if the city continues to grow in income and population, water price should be expected to increase as a result of increasing demand coupled with the inevitable convergence of withdrawal with MSY or aquifer failure. If users perceive a problem of future scarcity and if there are privately-held rights a futures market in water could develop, in which the community's current estimate of the present value of the future water price would be expressed in a current spot price. Then an "arbitrage condition" can be expressed as:

$$P_{(t+n)} = P_t\ (1+rn) \tag{4}$$

where P_t is the current price of water, $P_{(t+n)}$ is the current price for a water right dated n years ahead, and r is the social rate of discount. From (4),

$$r = [(P_{t+n}/P_t) - 1]/n \tag{5}$$

which is the well-known rule of Hotelling (1931) for equilibrium in asset markets. Let the social rate of discount equal the rate of return on the numeraire asset ($r > 0$), let the mineable stock of water be S_O at $t=0$, and let $W_t = D(P_t)$ be the market demand curve for water. Inverting the demand function, set

$$P_t = B(W_t) = D^{-1}\ (W_t). \tag{6}$$

Then gross consumer surplus is given by the integral

$$\int_{O}^{W_t} B(W_t)\ dW_t \tag{7}$$

The problem is to select the path of W_t so as to maximise consumer surplus subject to constraints governing residual stocks, non negativity of W_t, and a requirement that the sum of all future extractions over and above the renewable stock must equal the mineable stock. Along the optimal path representing an inter-temporal competitive equilibrium, the marginal social valuation of water would be constant when looked at from date $t = 0$. The entire portfolio of time-dated rights to extract water is, by assumption, traded at $t=0$. In practise, perfect foresight amongst participants in the water market would not be necessary: it is possible to envisage a short-term market in water rights which incrementally guaranteed constant present value prices. It is, however, necessary (both mathematically and from the point of view of welfare), that the initial price is "correct". Denoting change in price as ΔP_t, it can be shown that $r = \Delta P_t/P_t$.

The problem of inter-temporal equilibrium is complicated by the introduction of changing costs of extraction over time. To take account of this, a new form of the arbitrage equation is

$$P_{t+n} + \Delta C_{t+n}/W_{t+n} = P_t(1 + rn) \qquad (8)$$

where $\Delta C_{t+n}/W_{t+n}$ denotes a reduction in the unit cost of extraction costs during the period (t, t+n), due to the fact that the additional marginal unit was not extracted at time t. The Hotelling rule can be obtained as

$$r = (\Delta P_t/P_t - (\frac{\partial(C_t/W_t)}{\partial S_t})/P_t \qquad (9)$$

where S_t is the residual mineable stock at time t. The cost function, which might be quite complicated, is not discussed further here.

We conclude that where an urban area is utilising a single aquifer as a sole source in Stage III, with a declining resource stock, achievement of inter-temporal equilibrium in water assets and an optimal state trajectory is conditional on (i) correct initial pricing for the resource flow and (ii) equating the rate of change in water price with the social rate of discount, through continual modification of withdrawals, following equation (9).

The city of Tucson, Arizona, and surrounding agricultural settlements provide an example of Stage III development. These overlay a deep aquifer as described by the simple model (Martin et al 1984). This area has been defined as an Active Management Area (AMA) by the Arizona Groundwater Management Act of 1980, by which the AMA must achieve a stable level of groundwater withdrawal by the year 2025. The AMA is operating in Stage III with the water table dropping every year.

Since the 1940's population of the AMA has grown at increasing rates, from around 95,000 to 630,000 (ADWR, 1984). Agriculture has been declining, partly as a result of poor conditions, but also by conversion of land to urban uses. Under the 1980 Act no new agricultural land may be irrigated, and historical agricultural water use may be transferred to urban use if agricultural land is retired from production.

What does the general model tell us about the Tucson area? First, an inter-temporal model based on maximising discounted agricultural income is plainly irrelevant. Second, even without growth in population and economic activity, but allowing for income growth at the existing population size, agricultural use must eventually be eliminated, unless additional supplies are obtained from outside the area. Third, at the current rate of mining water supply from the AMA could be exhausted in about 100 years (Martin and Ingram, 1985), so per capita urban use must also eventually decline in the absence of water importation. Fourth, in Stage III, for given demand characteristics, appropriate pricing is necessary for determination of an economically efficient inter-temporal extraction policy. Of course, our assumption of full marginal cost pricing in reality would be well above the historical average cost pricing schemes that most utilities actually use. To the extent that utilities are currently pricing below direct, unsubsidised unit costs, increased prices would be helpful in working towards stability. But nothing short of Hotelling-type pricing with adjustments for future cost complications, can be claimed to be inter-temporally efficient. With a non-recharging aquifer such as that of the AMA the effect would be to progressively reduce the withdrawal rate until alternative, high-cost sources became economically competitive. The effect is thus similar to that of Burt, except that water pricing under conditions of shifting demand is an explicit part of the optimisation problem.

An alternative source for Tucson water supply is the Central Arizona Project (CAP), recognised as the most expensive water development in the history of the USA. It appears that this scheme will be completed. Even so, Martin et al (1986) estimate that economic and political forces will move the aquifer into Stage IV, despite very restrictive water use regulations that have been mandated by the 1980 Act. Marginal value of water will be very high (Martin and Thomas, 1986), and direct, current marginal cost will remain lower than that of alternative supplies. If water pricing along asset equilibrium principles turns out to be politically infeasible, and given the relative weakness of technical change and educational programs (Martin et al 1984), the only remaining, effective demand management policy would be planning controls on population growth and economic structure.

3.5 Stage III with land subsidence: the case of Bangkok, Thailand

The problems associated with groundwater use in the Bangkok region have been reviewed in Sharma (1986), on which most of the following discussion is based. Metropolitan Bangkok and its surrounding region are considered jointly for development and management of urban water supply. Population has grown rapidly, from 2 million in 1958 to 6 million in 1981. This has led to rapid growth in water use, which is expected to continue in future, possibly doubling by the year 2005. According to Sharma, 47% of total water use in metropolitan Bangkok came from surface sources, mainly the Chao Phraya River, and the remainder from groundwater extraction. Roughly two thirds of groundwater withdrawal was through private wells. Total groundwater use in 1982 was about 520 x 10^6 m^3, which exceeded the sustainable yield of about 220 x 10^6 m^3 yr^{-1} from the Lower Chao Phraya River Basin. Thus the aquifer is operating within Stage III.

Apart from excessive drawdowns in piezometric levels, problems of major environmental significance are land subsidence, saltwater encroachment, and increased flooding risks. Visual evidence of land subsidence is found in many places in Bangkok. For example, the ground surface surrounding many high-rise buildings has subsided, deep well cases protrude above ground, and shops sit well below street levels because roads and sidewalks have been built up layer by layer. Unless subsidence is halted large areas of the city will be below sea level. Frequent floods will cause problems of sanitation, hygiene, and traffic jams, damage to railway lines, buildings, drainage and sewerage systems, and collapse of well casings. Groundwater overdraft is recognised as the cause of the problem. Land subsidence is irreversible. It can however be halted by reducing or stopping groundwater extraction.

Without greater knowledge of the policy making process and economic conditions of the Bangkok region the authors do not wish to make specific suggestions about policy. However, the Bangkok case provides an example of the need for analysis of the Stage III policy for extraction from the particular aquifer in terms of a two-good, two-source model incorporating a discontinuous relationship between the groundwater withdrawal rate and the incidence of land subsidence costs rather than through some variant of the single-aquifer Hotelling model. To the extent that plans for public water supply in Bangkok include a cessation of pumping and development of alternative sources, this is clearly recognised by the authorities. However, the large residual withdrawal by private extractors poses extremely difficult problems for future management, and emphasises the close link which needs to be established between water markets, common property access provisions, and groundwater mining strategy.

4 CONCLUSION

A simple model of the possible stages of aquifer development was used as a basis for discussion of economic decisions about choice of the future state trajectory for a groundwater system, concentrating on issues which typically arise in the context of groundwater used for urban supplies. It was demonstrated that single-aquifer, single-industry models are of limited use for evaluation of urban groundwater development. In this area the resource allocation problem often involves continuously rising willingness to pay for water and non-continuous or irreversible externalities. These factors variously imply comparison between alternative sources, assessment of the efficiency of water markets in allocation, and valuation of externalities such as the depletion of wetland or land subsidence. Even where the urban area is totally dependent on a single aquifer, as occurs in some arid regions, the traditional single-industry "production" model of groundwater development is inadequate because it leaves out of account demand shifts, and ignores water pricing or demand management as control variables, thus optimising intertemporally with respect to producer surplus, but not with respect to consumer surplus. Asset equilibrium theory provides an alternative, theoretically superior basis for groundwater extraction policy in the depletive stage, which links the choice of aquifer state trajectory explicitly to price signals in the water market. Adoption of this principle is likely to lead to conservation of limited groundwater resources, and to an economically more efficient and smoother transition to possibly high-cost alternatives such as long-distance interbasin transfers or desalination.

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