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Optimal Temporal and Spatial Scheduling of Arid-Region Water Supply Projects with Nonrenewable Groundwater Stocks

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Abstract: Faced with explosive population and business growth, arid-area cities such as Las Vegas, Nevada, are scheduling water supply projects far into the next century. The city now relies on Nevada's small share of the Colorado River and meager local renewable water supplies. Substantial deposits of ground water of adequate quality located at some distance from the population center are a possible supply option. This paper develops a model for analyzing the economic feasibility and the optimal investment path for water supply for Las Vegas. We forecasted residential, industrial, and other municipal demands and the schedule of increasing costs of the water supply options. A dynamic programming model determines the optimal groundwater pumping projects in temporal and spatial dimensions along with other static water supply projects, and determines the quantity and price of water available in the region. When groundwater pumping is a supply option, the optimal rate of groundwater usage must account for the increasing costs of pumping from greater depths. Dynamics of groundwater usage is found to alter the sequence that these projects are scheduled to met Las Vegas water demands.

Introduction

Rapid population growth in the arid southwestern United States continues to increase municipal and industrial water demands, most noticeably in the major metropolitan centers. Local options for increasing water supply are typically limited: most often surface flows are fully appropriated, and groundwater withdrawals frequently exceed perennial yields, leading to overdraft. With little possibility of increasing local supplies in the metropolitan centers, surrounding rural regions are inevitably viewed as the potential supply sources.

One of the most rapidly growing regions of the U.S. is the Las Vegas area in southern Nevada. Limited population and agricultural development historically allowed the region to meet water demands from local ground water resources and then from Nevada's 300,000 acre foot annual entitlement to Colorado River water. Anticipated population and business growth in the greater Las Vegas region now suggests that this fixed entitlement of surface water will be insufficient to meet future desired levels of water use.

However, alternative supplies are available, particularly from outlying groundwater basins. Given the arid climate, the natural recharge to these aquifers is quite limited. Hence, any extensive ground water exploitation would likely involve mining of water stocks with the consequent water table declines and increasing pumping cost. Such trans-basin imports would therefore likely be economically and environmentally costly.

Our study contributed to the assessment of the proposed Yucca Mountain nuclear waste depository, planned for a site some one hundred miles northwest of Las Vegas. The specific aims of our research were to forecast the equilibrium price and quantity of water used in southern Nevada over a fifty year planning period, and to establish the optimal location and rates of possible extraction from ground water deposits, particularly those deposits near the proposed depository site. In order to achieve this aim, it is necessary to establish the optimal schedule in space and time of investments in water supply projects. We extend previous models of optimal urban water supply by incorporating the temporal as well as spatial aspects of water supply investments and the dynamics of groundwater depletion into our analysis.

Previous Research

Our study draws on three strands of the water economics literature: (a) surface water supply to meet urban growth, (b) the optimal temporal investment in water supply (in this case ground water extraction) capacity and (c) the optimal temporal allocation of nonrenewing ground water stocks .

Economists studying western water supply issues have given much attention to the issue of finding least-cost solutions to meeting growing urban water demands. Any such economic evaluation, of course, calls for consideration of both costs (supply) and benefits (demand), so as to identify if net benefits are positive and who gains and who loses. We sketch this large literature by tracing what seem to be the principal contributions to the evolution of the methodology. An initial approach (as still reflected in the U. S. Government's *Principles and Guidelines, 1983)* was to analyze the economic benefits and costs of supplying a fixed predetermined supply of (usually surface) water from proposed investments in dams, reservoirs, conveyance and treatment facilities. Hirshleifer, *et al*. were among the first to argue that transferring water from existing but low-valued uses might be more economical than new projects, proposing that purchasing irrigation water rights from the Imperial Valley (on the California-Mexico border) would be preferable to constructing the Feather River Project to bring northern California water to southern California. Howe and Easter set out an analytic framework for evaluating large scale interbasin transfers of water, emphasizing the importance of the opportunity costs of water (in both instream and offstream uses) in the areas of origin. Cummings introduced a formal optimization procedure (linear programming with nonlinearities represented by piecewise linearization) to the study of interbasin transfers, considering a proposal to move water from areas of plentiful supply to rescue an irrigated area depleting its ground water supplies in northwest Mexico. Cummings also incorporated an evaluation of the optimum rates of extraction of ground water in the target area. Vaux and Howitt formulated a nonlinear trade model linking five demand and eight supply sectors in central and southern California to show that with minor exceptions, reallocation from existing uses is more economical than development of new supplies over a forty year planning period. Booker and Young (see also Booker) developed an optimization framework for analyzing market solutions to increasing demands for Colorado River waters, incorporating mineral water quality (salinity) and instream demands.

Another strand of water management literature relevant to our study is that focusing on the optimal temporal allocation of ground water. Analysis of the optimal rates of investment in ground water supply capacity and rates of extraction pose problems of spatial and temporal dimensions. The cost of water from each source depends on its aquifer characteristics and on the cost of pumping, transporting and treating the water. Population, income and business growth causes water demand to vary with time. Water costs by source vary with time as aquifers are depleted and water tables decline. Hence, water supply projects must be scheduled to anticipate growing water demands. Early approaches assumed that the policy decision was only to choose an optimal annual pumping rate, a rate that once selected, would remain constant or fixed for the entire planning period. A more rigorous solution (developed first by Burt), incorporates dynamic optimization methods. The optimal annual pumping rate is, for any year, derived from a decision rule, which is defined as a function current aquifer stocks. (The decision rule is further conditional, as was the simpler formulation, on demand, cost, interest rate, and aquifer parameters.) The dynamic optimization approach has been applied to several case studies (see Feinerman and Knapp; Provencher and Burt). Noel, et al. extended the analysis to a multiple aquifer, multiple demand source case.

To address such questions for the southern Nevada case, a dynamic programming approach is used to project future welfare maximizing water use patterns. The projected water uses and transfers are used to examine economic impacts of growing metropolitan water demand on rural southern Nevada communities.

A Dynamic Regional Trade Model

Economic trade models may be used to estimate future water use and value when transport between basins is possible (e.g. Vaux and Howitt). The approach is that used to estimate market outcomes in a system with multiple producers and consumers. Determining equilibrium water use in a supply and demand setting with multiple sources and uses is most conveniently achieved by solving a dynamic program.. Figure 1 illustrates the application of the framework to southern Nevada.

An objective function maximizes net benefits from water use:

$$Maximize\ W = \sum_{i,j,t} d_t \left(V_{jt} - C_{ijt} \right) \tag{1}$$

where V_{jt} (Q_{jt}) is the total benefit to user j at time t of water use Q_{jt} , C_{ijt} (D_{it}, X_{ijt}) is the cost of supplying use j in time t using source i, given aquifer drawdown D_{it} and the total diversion from source i delivered to user j in time t X_{ijt}, and $!_t = 1 / (1+r)$ is the discount factor at time t used to relate future value to present value.

The dynamic program is optimized subject to a series of constraints. Water supplies and uses are implemented into the dynamic program with mass balance equations to match deliveries X_{ijt} from supply sources i to uses Q_{jt}:

$$\sum_i X_{ijt} = Q_{jt} \tag{2}$$

Sources and uses are matched -- only certain sources i may deliver to uses j (i.e. the Virgin River is not included as a potential supply source for the regional groundwater basins). The total annually

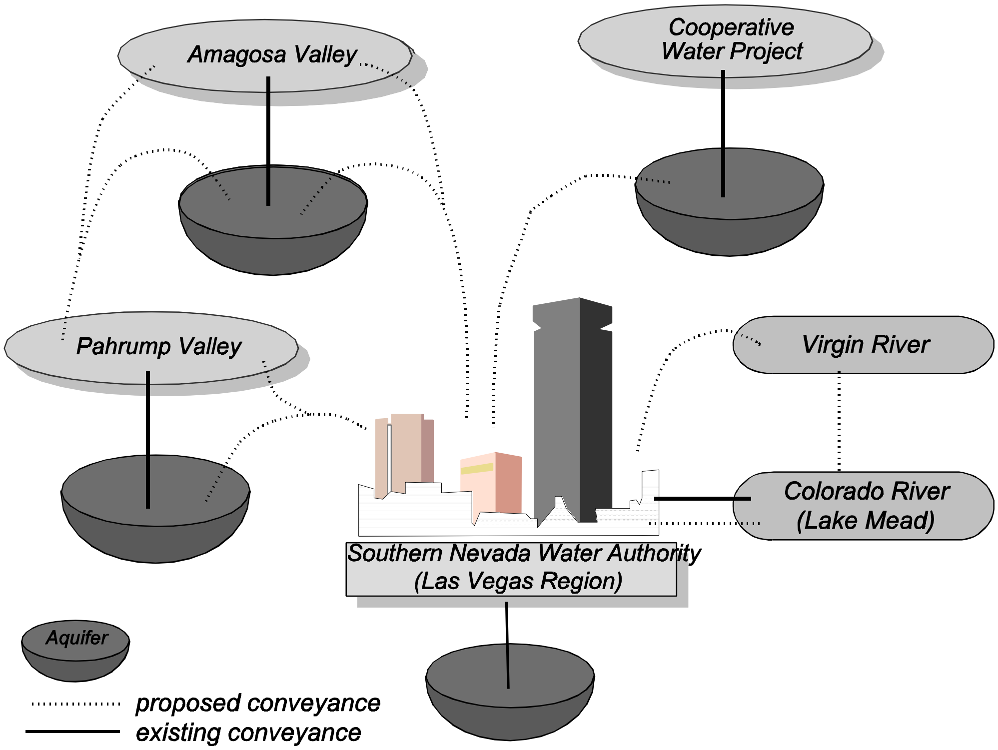

Figure 1. Schematic representation of the regional trade model.

available consumptive use x_i^o from any given source is given by

$$\sum_j X_{ijt} \le x_i^o + R_{it} \tag{3}$$

where R_{it} is the total return flow to source i given by

$$R_{it} = \sum_j (1 - e_{ij}) Q_{jt} \tag{4}$$

Total return flows are a function of e_{ij}, the consumptive use efficiency in use Q_{jt} from source i. For example, a unit export from a Nevada groundwater basin to the region served by the Southern Nevada Water Authority (SNWA) results in return flows $(1\text{-}e_{CR,SNWA})$ to the Colorado River (CR). Equation (4) may in practice disaggregate $Q_{j,t}$ to represent local conditions. For example, Ash Meadows in Amargosa Valley (AV) generates no return flows, so $Q_{AV,t}$ in (4) includes only use from pumped water $Q^e_{AV,t}$. In the case of overdraft of groundwater sources, x_i^o is greater than perennial yield and drawdown of groundwater levels and stocks must also be considered. Groundwater elevation decreases with cumulative net overdraft. The decrease in elevation, or drawdown D_t is given by

$$D_t = D_{t-1} + (d_i / y_i)(\sum_j X_{ijt} - R_{it} + O_{it} - y_i) \tag{5}$$

where d_i is a parameter giving the drawdown per unit overdraft equal to perennial yield y_i, and O_{it}

is the outflow, if any, from the basin. In practice, O_{it} is zero if use is equal or greater than perennial yield. If net use is less than perennial yield, the second term in equation (5) is zero, and outflow plus net use equals perennial yield.

Total stock level $X_{it}^{S} = X_{i0}^{S}$ initially, and is given in year t by

$$X_{it}^{S} = X_{it-1}^{S} + Y_i - \sum_j X_{ijt} - O_{it} \tag{6}$$

where X_{it}^{S} is the groundwater stock in period t-1, Y_i is the perennial yield, and O_{it} is the outflow from groundwater basin i in year t.

Benefit and Cost Functions

A constant elasticity form is used for the benefit function:

$$V_{jt} = V_{jt}^{o} \left(\frac{Q_{jt}^{e}}{q_{jt}^{o}}\right)^{\beta_{jt}} \tag{7}$$

where, V_{jt}, Q^{e}_{jt} is the total economic use by source j in year t, q^{o}_{jt} is the projection of economic uses at current price levels p^{o}_{t}. The exponent β_{jt} is given by

$$\beta_{jt} = \left(\frac{1}{\eta_{jt}}\right) + 1$$

where η_{jt} is the price elasticity of demand, and

$$V_{jt}^{o} = \frac{p_t^{o} q_{jt}^{o}}{\beta_{jt}}$$

Total use Q_{jt} at each location j includes non-economic uses q^{n}_{jt} and economic uses $Q^{e}_{jt\,;}$ non-economic uses are required; that is $Q_{jt} \geq q^{n}_{jt}$.

Costs C_{ijt} are long run costs which include pumping, conveyance, treatment, and distribution costs of utilizing source i to supply use j in period t. Costs may also include foregone benefits in alternative uses exogenous to the programming problem. This is necessary in the case where rights to water use can either be bought or sold under market-like institutions. An example would be the cost to SNWA of compensating a Colorado River Basin agricultural user in return for their water rights. Costs are calculated as

$$C_{ijt} = (c_{ij}^{o} + c_{ijt}^{x} + c^{p} D_{it}) X_{ijt} \tag{8}$$

where c^{x}_{ijt} are opportunity costs of uses exogenous to the programming problem, c^{p} are pumping costs per unit drawdown) from existing conditions), and c^{o}_{ij} are all other costs of delivering water from source i to final use j.

Data

Development of the empirical information to support the regional trade model is discussed in detail in the Woodward-Clyde report, Water Resources Assessment: Yucca Mountain Project. Primary data sources and general approaches to utilizing these sources are discussed here.

Costs

Estimating future regional use and economic value of regional water use requires supply costs for potential supply sources. Because economic demands are given as the demand for water delivered to the end user, all transport costs to the particular user must also be included.

Regional conveyance costs represent the largest economic barrier to utilizing groundwater to meet projected regional supply shortfalls. (Environmental constraints in Amargosa Valley are currently an even larger barrier to development.) Similarly, most potential supply sources for SNWA needs suffer from similarly high conveyance costs.

The cost estimates for such hypothetical future projects are very uncertain. In most cases detailed engineering studies have not been performed, and local site conditions which may either increase or possibly decrease costs are not known. The potential Nevada supply sources (Amargosa Valley, Pahrump Valley, and Cooperative Water Project groundwater, and a Virgin River dam and pipeline) do not have detailed engineering cost estimates, and the costs reported here must be considered speculative. Given these considerations, there is little basis for distinguishing on a cost basis between the major within-state supply options which are presented here. Across a number of Nevada groundwater basins, including Amargosa and Pahrump Valley, total delivered unit costs differ by no more than 15% (in 1996 dollars) from the more recent estimates presented above.

Supply sources outside Nevada have similarly speculative costs. If Colorado River supplies were available at their economic opportunity cost (their value in foregone -- typically agricultural -- uses), then SNWA would have little reason to look at alternative Nevada supplies including Amargosa Valley. Such (out of state) supplies are not available at present, however, and the institutional changes required to allow such transfers to water use in SNWA may or may not occur.

One possibility of using Colorado River water would involve exchanges with southern California. SNWA would operate or finance desalination plants in southern California, and would in return receive a right to a commensurate increase in its consumptive use of Colorado River water. While institutional barriers could likely be overcome, the costs of large scale desalination remain highly uncertain.

Environmental considerations are not systematically considered, except for the Ash Meadows and Devil's Hole areas in Amargosa Valley. It is likely that within-state projects such as a Virgin River pipeline would be required to address significant environmental impacts. Cost implications, or the probabilities of such concerns making specific projects infeasible, are unknown.

Estimated economic demand in this study does not consider water quality. One potential supply source, piped Virgin River water, has very high salinity which would likely cause damages in municipal uses. This damage is included here as an opportunity cost of using such supplies. Booker and Young estimate annual household damages of $0.263 per mg/l total dissolved solids (1989 $). The approach is to estimate damages of using Virgin River water in excess of those presently incurred from use of Colorado River water.

Water Demand Projections

Water demand projections use existing levels of use, with future use levels based primarily on expectations of future population growth. The projections do not include consideration of available supply or costs. Starting from these projections, economic demand functions are constructed for use in the regional water supply and demand analysis.

$$p = p^{0}\left(\frac{x}{x^{0}}\right)^{\frac{1}{\eta}}$$

Economic demand for water use is assumed to follow the constant elasticity functional formwhere p is the marginal willingness-to-pay for additional use, p_0 is the current price for consumptive use, x is the total quantity of consumptive use, x_0 is the current quantity of consumptive use, and eta is the price elasticity of demand. This form is particularly convenient in applying non-economic water use projections, as x_0 becomes simply the projected use, and all other parameters are unchanged. If price changes are also included in the projection, then this can also be included through a change in the parameter p_0. The average price for current water use is used as the estimate for p_0 in the base year.

Projecting future demand in southern Nevada can only be described as speculative. Extremely rapid population growth has repeatedly caused past population estimates to significantly underestimate current conditions. Conversely, present population growth rates could slow more rapidly than now projected, causing present projections to significantly overestimate actual future conditions.

The most recent Southern Nevada Water Authority (SNWA) forecasts of future use are used as the basis for SNWA demand projections. These projections are supplemented by a less current water demand forecast to year 2100 (Planning and Management Consultants). Figure 2 shows projected water use in the SNWA service area and the underlying population projection (Center for Business and Economic Research) used by SNWA in these projections. The difference between 1994 and 1997 projections is striking: under the assumption of only existing conservation plans, projected water use is 52% higher in the 1997 report than that given in 1994.

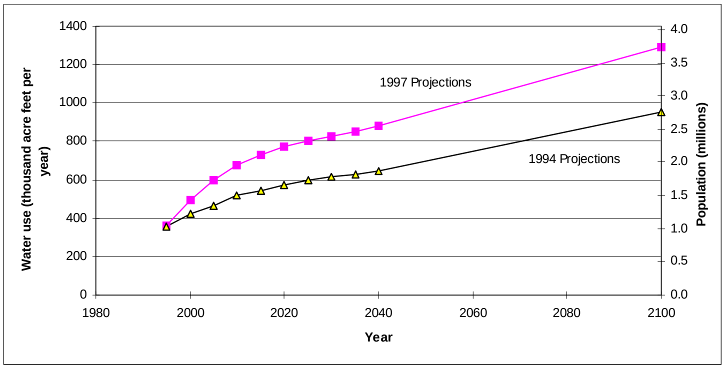

Figure 2. Alternative population and water use projections for southern Nevada. (Sources: Planning and Management Consultants, 1994; Southern Nevada Water Authority, 1997; calculations by the authors.)

Results

Supply Assumptions

In developing the regional water use and value projections presented below, a single representative scenario was used. Table 1 summarizes the critical supply assumptions. The scenario is indicative of possible future conditions. In particular, a modest additional supply of Colorado River water is assumed, and significant overdraft of groundwater basins is allowed, though not required. No overdraft in Las Vegas Valley is allowed due to the potentially high subsidence costs.

Cost estimates for future supplies are particularly speculative. These estimates are not based on detailed investigations, and utilize a low real discount rate (3%). It is therefore possible that the cost estimates are systematically too low. Because future conditions are unknown, the scenario presented here is not a prediction. Rather, it is a projection of one possible future with respect to regional water use.

Table 1. Critical parameters defining the scenario. Maximum use is the consumptive use limit, and average costs are for final delivery within the Southern Nevada Water Authority Region. Safe yield applies to groundwater basins.

Source	Maximum Use (af/yr)	Safe Yield (af/yr)	Unit Cost ($/af)	Consumptive use efficiency (%) for Return Flow to (a)	
				Colorado River	Local groundwater
Colorado River (existing)	300	n/a	503	63%	n/a
Colorado River (speculative)	100	n/a	638	63%	n/a
Las Vegas Valley groundwater	53	53	277	0%	73%
Cooperative Water Project	362	181	882	63%	n/a
Pahrump Valley	60	20	848	63%	75%
Amargosa Valley	77	28	835	63%	75%
Virgin River pipeline	70	n/a	1233	63%	n/a

Notes:

(a) Refers to percentage delivered which is consumptively used. Return flow is to the local groundwater basin, or to the Colorado River.

Regional Water Use Projections

Given projections of continued rapid population growth, the southern Nevada region (SNWA) will demand significant new water sources within the next 10 to 20 years (Table 2). The most likely new sources (complementing per capita use reductions resulting from rising prices and conservation programs) are additional withdrawals from the Colorado River, or imports from Nevada groundwater basins. The benefits of additional water supplies to SNWA water users will exceed the substantial costs of providing these supplies.

The economic value of regional water is projected to increase throughout much of the study period. Given the engineering cost estimates available for this study, and the assumption that no more than an additional 100 thousand acre feet (kaf) will be available from Colorado River sources, (marginal) benefits to SNWA users will increase to cover the costs of not only additional Colorado River supplies, but imports from state groundwater basins. In particular, *benefits in SNWA uses would cover costs of importing water from state groundwater basins*, starting as soon as 15-20 years from today. While the timescale is critically dependent on rates of population growth in southern Nevada, additional supply sources are likely to be exploited if future Colorado River deliveries are limited.

Table 2. Projected equilibrium price and water allocation by source for Southern Nevada Water Authority customers.

Year	Price (delivered to final use)	Colorado River (existing)	Colorado River (speculative)	Las Vegas Valley groundwater	Cooperative Water Project	Pahrump Valley	Amargosa Valley
	($/af)	(kaf)	(kaf)	(kaf)	(kaf)	(kaf)	(kaf)
1995	503	354		72			
2000	565	488		72			
2005	638	488	96	72			
2010	706	488	159	72			
2015	726	508	159	72		1	33
2020	742	524	159	72		7	54
2025	742	533	159	72	18	6	54
2030	742	544	159	72	33	7	54
2035	742	554	159	72	44	14	54
2040	742	565	159	72	61	16	54

Discussion

Several clear conclusions are possible. Regional economic demand and supply indicates there are economic incentives to exploit regional groundwater basins at rates which could cause significant drawdown and discharge impacts (Table 3). Certain groundwater basins (e.g. Amargosa Valley) are not currently under consideration as potential supply sources because of the potential for such impacts. Economic incentives to exploit Nevada groundwater basins for export to municipal uses in southern Nevada exist only if Colorado River supplies are unavailable. Colorado River water is potentially available in sufficient quantity and at a price which would eliminate all economic justification for exploiting Nevada groundwater in the foreseeable future. It is unknown whether such water will become available; this would require other basin states agreeing to limit their state's use of Colorado River.

Immediate barriers to export of state groundwater to southern Nevada is financial cost and the potential for environmental impacts. For example, institutional protection by federal agencies to protect Ash Meadows spring flows will limit any immediate development of Amargosa Valley groundwater for regional use. It is unknown how such environmental protections will be weighed against economic incentives for development in the future. Further, it is also unknown whether mitigation strategies could be developed which would allow for future development while protecting environmental values.

Table 3. Groundwater use and impacts.

Year	Gross Pumping (kaf/yr)[a]			Local Return Flow (kaf/yr)		Net Use (kf/yr)		Basin Drawdown (feet)	
	AV[b]	PV[c]	CWP[d]	AV	PV	AV	PV	AV	PV
1995	32.1	23.6		3.8	5.9	28.3	17.7		
2000	32.5	25.1		3.9	6.3	28.6	18.8		
2005	32.2	22.9		3.8	5.7	28.4	17.2		
2010	32.3	22.9		3.8	5.7	28.5	17.2		
2015	61.0	26.4		2.8	6.4	58.2	20.0	10.4	
2020	79.0	34.4		2.0	7.0	77.0	27.4	27.4	7.4
2025	78.9	39.2	17.5	1.9	8.4	77.0	30.8	44.5	18.2
2030	78.9	47.8	33.1	1.9	10.2	77.0	37.6	61.5	35.8
2035	78.9	62.6	44.4	1.9	12.2	77.0	50.3	78.5	66.1
2040	78.9	74.7	60.5	1.9	14.7	77.0	60.0	95.5	106.1
Safe Yield (kaf/yr)	28	20	181						

Notes: [a] Includes spring discharges of 17 kaf/yr at Ash Meadows in Amargosa Valley.
[b] Amargosa Valley; [c] Pahrump Valley; [d] Cooperative Water Project.

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