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Measuring the Long-Term Regional Benefits of Salinity Reduction

Gregory W. Characklis, Ronald C. Griffin, and Philip B. Bedient

Approaches for evaluating salinity management benefits are generalized and extended to incorporate consideration of desalination and long-term changes in salinity concentration and water use patterns. Previous research indicates urban users incur the vast majority of salinity-related damages in affected regions, suggesting municipalities may benefit by considering mitigating actions independent of agriculture. However, previous studies have included no consideration of desalination. Earlier studies have also considered stepped increases in salinity, assuming a single future concentration when estimating the long-term benefits of salinity reduction, an approach inconsistent with the incremental nature of these increases. Long-term changes in water use patterns (urban vs. agricultural), when considered at all, have often been treated in the same stepwise fashion. For this analysis, a suitable region is selected and the benefits of a hypothetical salinity management program are estimated using the approach described. These results are then compared with those obtained through the use of several previous methods. Findings suggest that consideration of desalination and incremental variations in salinity and water use patterns can substantially lower the estimated benefits of regional salinity management programs.

Key words: benefits, regional water resource modeling, salinity, water quality management

Introduction

Rising salinity is an increasingly pervasive global problem with an ability to significantly affect municipal and agricultural water users. Within agriculture, increasing salinity levels can lower irrigated crop yield (Letey, 1993; Maas, 1990; Ayers and Westcott, 1985; Letey, Dinar, and Knapp, 1985; Maas and Hoffman, 1977) while municipal users incur economic damages related to accelerated degradation of infrastructure and increased use of tap water substitutes (e.g., bottled water) (M.Cubed and Co., 1999; Ragan, Makela, and Young, 1993; Tihansky, 1974b; Metcalf & Eddy, Inc., 1972; Patterson and Banker, 1968). Concerns over these economic impacts have motivated state and federal agencies to consider or pursue salinity management programs in several western watersheds (e.g., Colorado, Red, Rio Grande), and federal guidelines (U.S. Water Resources Council, 1983) require that such programs be subjected to cost-benefit analysis.

Calculating program costs is challenging, but conceptually straightforward. Evaluating benefits is more difficult. Benefit estimation requires the calculation of two values: (*a*) the relative reduction in salinity brought about by the program, and (*b*) the benefits

Gregory W. Characklis is assistant professor, Department of Environmental Sciences and Engineering, School of Public Health, University of North Carolina at Chapel Hill; Ronald C. Griffin is professor, Department of Agricultural Economics, Texas A&M University, College Station; and Philip B. Bedient is professor, Department of Environmental Science and Engineering, Rice University, Houston, Texas.
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that accrue as the result of such a reduction (i.e., avoided damages). The first step is accomplished through hydrologic modeling. The second step requires consideration of a broad range of factors and is the central focus of this work.

A number of detailed models have been developed for estimating the effects of salinity on crop yield (Shani and Hanks, 1993; Warrick, 1989; Letey and Dinar, 1986; Letey, Dinar, and Knapp, 1985). Relationships have also been developed to assess the additional costs that elevated salinity imposes on specific municipal activities (M.Cubed and Co., 1999; Ragan, Makela, and Young, 1993; Tihansky, 1974a,b; Metcalf & Eddy, Inc., 1972; Patterson and Banker, 1968). Both types of relationships have been used in another class of studies which provide overall regional estimates of salinity-related damages (Bookman-Edmonston Engineering, Inc., 1999; Lee and Howitt, 1996; Booker and Young, 1994; Lohman et al., 1988; Gardner and Young, 1985, 1988; Anderson and Kleinman, 1978). Each of these regional salinity studies has found that the bulk of damages occur in the municipal sector, even though the majority of regional water use in each case has been agricultural. The Colorado River, for example, has experienced significant salinity increases in recent decades, and while irrigation dominates regional water use patterns (> 90% of total use), municipal salinity damages have been estimated to account for as much as 85% of the regional total (Lee and Howitt, 1996; Gardner and Young, 1985, 1988; Anderson and Kleinman, 1978). These results suggest that a change in the fraction of municipal water use, or a change in technology that mitigates municipal damages alone (i.e., desalination), could have a significant impact on the benefits of regional salinity management. Changes in both areas are probable over the long lifespans of salinity management projects, but these changes have received little attention in previous work.

Desalination is important to consider as declining costs have made it increasingly attractive, particularly for applications involving moderately saline waters (< 2,500 mg/l) (Wangnick, 2000; Morin, 1994). While traditionally viewed as expensive, recent work has found the reduction in municipal damages brought about through desalination can exceed its additional costs when source water salinity is as low as 1,000 mg/l (Characklis, 2004). The benefits of desalination accrue primarily to the salt-sensitive municipal sector; thus its implementation may significantly alter the regional benefits of salinity management. (Note: Desalination can benefit all downstream users, agricultural or municipal, if less saline municipal wastewater were to improve the quality of a common water body.)

In addition, given that water transfers from agricultural to urban use are now common in saline portions of the West, continued reallocation promises to impact the long-term benefits of a management program. Nonetheless, few studies have included an examination of changing water use patterns, and those analyses have generally represented such patterns as a step change between current conditions and those expected to exist at the end of program life. Changes in salinity concentration have often been represented as a similar step increase. Because changes in both salinity and demographics are usually incremental, this stepped approach may provide less representative benefit estimates.

This work incorporates desalination opportunities and incremental changes in salinity and water use patterns into regional estimates of salinity management's long-term benefits. Rising salinity is an issue likely to be faced by a growing number of watersheds, both in the United States and abroad. Research that aids in the development of more robust means of quantifying the regional impacts of rising salinity is therefore likely to have increasing application as policy makers seek cost-effective mitigation strategies.

Methods

Here the benefits and costs of regional water use are modeled for multiple time periods over a range of municipal and agricultural activities, while recognizing the differing salt sensitivities of each water-using group. The regional net benefits of water use are calculated annually over a series of years under two different sets of conditions, one with a salinity management program in place and the other without a program. The annual values in each series are then discounted and summed to provide measures of the net present value (NPV) of water use under "with" and "without" scenarios. The difference between these two NPV values constitutes the benefits of reducing salinity levels, a value that can then be compared to the present value of program costs.

Throughout this work, modifications are made to existing approaches of computing municipal and agricultural salinity damages (e.g., shorter appliance life, lower crop yields), but these calculations are based largely on relationships developed in earlier studies and are not a point of departure from prevailing literature. Rather, it is consideration of the nature and types of changes which may occur in technology and water use patterns that are significant and likely to have substantial consequences for the outcome of future benefit analyses (regardless of the methods used to estimate damages within individual activities). The methodology described is relatively data intensive, but it is sufficiently general to be applied to many regions. When doing so, however, it is important to note this approach requires the specification of region-specific trends related to rising salinity and shifting water use patterns—trends that will vary with a region's physical characteristics, demographics, and regulatory institutions.

Water Use Benefits

Base year demand functions for annual water use are specified for each activity (i) using a Cobb-Douglas form that expresses marginal benefits at the point of use, defined as "the tap" for municipal users and the field gate for agricultural users. Point-of-use consumption data for municipalities can be drawn from utility records (table 1), while those for agriculture are based on regional irrigated acreage data and empirical values for water use per unit area (q_{POU}, see table 2). All acreage producing the same crop is assumed to be homogeneous, and annual point-of-use consumption (Q_{POU_i}) for each irrigated activity ($i = n+1, n+2, ..., m$) is computed as:

(1) $$Q_{POU_i}(acre\text{-}feet/year) = A_i * q_{POU_i},$$

where i = index of water use activities, municipal ($i = 1, 2, ..., n$) and agricultural ($i = n + 1$, $n+2$, ..., m); A_i = regional area devoted to crop type i (acres/year); and q_{POU} = base year value for point-of-use irrigation in activity i (acre-feet/acre).

Demand functions are developed via point expansion (Jenkins, Lund, and Howitt, 2003) using empirically derived elasticities (ε), as well as known values for acquisition/delivery costs and point-of-use consumption, to calculate constants (α) for each municipal

Table 1. Base Year (1995) Model Parameters

i	Activity	Source Water Consumption, Q_{Source} (acre-feet/year × 10^3)	Irrigated Acreage, A (acres × 10^3)	Acquisition and Delivery Cost ($/acre-foot)	Demand Elasticity,[a] ε	Base Year Technology	Base Year Technical Efficiency, e_B	Conveyance Losses,[b] L
MUNICIPAL:								
1	Small	38.9	—	16.00	-0.32	Convent. Trtmt.	1.00	0.44
2	Large	106.4	—	16.00	-0.32	Convent. Trtmt.	1.00	0.24
AGRICULTURAL:								
3	Citrus	151.6	30.3	16.00	-0.4	Flood	0.5	0.2
4	Sugar Cane	224.0	40.0	16.00	-0.4	Flood	0.5	0.2
5	Vegetables	161.5	45.7	16.00	-0.4	Flood	0.5	0.2
6	Corn	88.8	47.4	16.00	-0.7	Flood	0.5	0.2
7	Field Crops	458.8	245.0	16.00	-0.7	Flood	0.5	0.2

[a] Municipal elasticities are evaluated at the tap, and agricultural elasticities at the field gate.
[b] Municipal losses include both river-to-plant and plant-to-tap losses; agricultural losses include river-to-field gate losses only.

Table 2. Salt-Sensitivity and Base Year (1995) Water Application by Crop Type

Crop Type	Salinity Threshold[a] (mg/l)	Salinity-Yield Slope[a] (%/mg/l)	Water-Yield Slope[b] (–)	Increased Irrigation[c,d] 1972–1995 (%)	Base Year ('95) Irrigation,[d] q_{POU} (acre-feet/acre)	Base Year Effective Water Application[e] (acre-feet/acre)	Evapotranspiration Maximum,[f] ET_{max} (acre-feet/acre)	Effective/ ET_{max} (–)
Citrus	770	0.021	1.20	71	4.0	4.5	2.9	1.5
Vegetables	1,020	0.012	1.10	25 to 40	2.8[g]	1.9	0.8[g]	2.5
Corn	1,090	0.019	1.25	12 to 50	1.5	1.1	1.3	0.8
Sugar Cane	1,090	0.009	1.20	N/A	4.5	3.7	3.5	1.1
Field Crops	4,480	0.015	0.87	0	1.5[h]	1.3	1.3[h]	1.0

Note: Parameters used in water-salinity-yield relationships (first three numeric columns) were developed by Letey, Dinar, and Knapp (1985).
[a] Maas (1990), Ayers and Westcott (1985); [b] Doorenbos and Pruitt (1975); [c] flood irrigation in all cases; [d] Texas Agricultural Extension Service (1972–73, 1990–96); [e] irrigation + seasonal precipitation × rainfall effectiveness factor [0.7]; [f] Texas Agricultural Extension Service (2000); [g] average of vegetable crops; [h] average of field crops.

and agricultural activity. The specification of these constants allows base year functions to be fully specified, such that:

(2) $$MB_{POU_i}^{Base}(\$/acre\text{-}foot) = \left[\frac{Q_{POU_i}}{\alpha_i}\right]^{1/\varepsilon_i}.$$

Base year demand endogenizes factors related to base year salinity levels, technology, and water use patterns, all of which must be modified to account for changing conditions in future years.

While the impacts of rising salinity are most easily evaluated at the point of use, water quality and availability are generally monitored at the source. Demand at the source also provides a common reference point for evaluating the net benefits of water use in both municipal and agricultural activities. In translating demand between these two points, it is important to consider conveyance losses (i.e., evaporation, seepage, leaks), as well as the water use efficiency of the technologies used in each activity. In agriculture, the efficiency of water application can vary from 0.5 (flood irrigation) to 0.95 (drip irrigation). Within the municipal sector, conventional treatment processes (i.e., flocculation-sedimentation-filtration) return essentially 100% of raw water as treated product, while desalination returns significantly less (typically 70% to 90%). Consumption at the point of use is related to consumption at the source by:

(3) $$Q_{Source_{ij}}(acre\text{-}feet/year) = \frac{Q_{POU_i}}{(e_j/e_{B_j}) * [1 - L_i]},$$

where j = index of water application/treatment technologies, $j = 1, 2, ..., p$; e_B = efficiency of base year application/treatment technology, $e_B \in [0,1]$ (–); e = efficiency of the current application/treatment technology, $e \in [0,1]$ (–); and L = conveyance losses between the source and point of use, $L \in [0,1]$ (–). This relationship is then combined with (2) to generate a base year marginal benefits function for water at the source, expressed as:

(4) $$MB_{Source_{ij}}^{Base}(\$/acre\text{-}foot) = \left[\frac{Q_{Source_{ij}} * (e_j/e_{B_j}) * [1 - L_i]}{\alpha_i}\right]^{1/\varepsilon_i} * (e_j/e_{B_j}) * [1 - L_i].$$

Because changes in salinity affect the marginal benefits of water use in activity-specific ways, base year demands for municipal and agricultural activities are modified differently. Moderate salinity concentrations (< 2,500 mg/l) do not appreciably affect water's solvent, cleaning, cooling, or waste conveyance properties; thus the utility of water in the vast majority of municipal uses remains largely unaffected. Small changes in demand may be experienced in areas such as drinking water (typically < 2% of municipal use) or urban irrigation (mainly turfgrass, which is unaffected by moderate salinity levels), but these are not likely to be significant. As a result, municipal demand at the point of use can be reasonably regarded as constant within the salinity range applicable here. Municipal demand for source water will be affected, however, if rising salinity motivates a switch from conventional to desalination technologies, as the latter are less efficient and require more source water to supply the same volume to the tap.

Desalination can significantly lower municipal damages relative to conventional processes, and while desalination remains more expensive, its costs are declining (Wangnick, 2000; Wiesner and Chellam, 1999). A comparison of the increased costs and reduced damages arising from switching between conventional treatment and desalination is undertaken as part of this analysis in the next section.

Municipalities vary both in terms of size and their makeup, so multiple municipal water demand functions can be specified for any region. For each municipal type i, using technology j, the annual benefits of water use at the source are calculated by integrating under (4), such that:

$$(5) \qquad Benefits^{Muni}_{Source_{ij}}(\$/year) = \int_0^{Q_{Source_{ij}}} MB^{Base}_{Source_{ij}}\, dQ_{Source}$$

$$= \alpha_i^{-1/\varepsilon_i} * \left(\frac{\varepsilon_i}{\varepsilon_i + 1}\right) * \left[(e_j/e_{B_j}) * [1 - L_i] * Q_{Source_{ij}}\right]^{[1+\varepsilon_i]/\varepsilon_i}.$$

In agriculture, elevated salinity has a direct effect on the marginal benefit of irrigation water, so steps must be taken to incorporate salinity impacts directly into demand functions. Most previous regional studies (Bookman-Edmonston Engineering, Inc., 1999; Lohman et al., 1988; Anderson and Kleinman, 1978) have used agronomic models that describe a linear relationship between yield and salinity while assuming a constant level of applied water (usually the theoretical evapotranspiration maximum, ET_{max}). Such approaches set aside irrigators' common practice of applying additional water to flush salts from root zone soil (i.e., leaching). Several regional studies have addressed this issue by incorporating models allowing for varying water applications (Lee and Howitt, 1996; Gardner and Young, 1985). A review of these studies, and the agronomic literature (e.g., Letey, 1993; Dinar and Knapp, 1986; Letey and Dinar, 1986), led us to select a model incorporating nonlinear yield-salinity responses over a range of water levels that extend both above and below ET_{max} (Letey, Dinar, and Knapp, 1985; Warrick, 1989).

The Letey, Dinar, and Knapp (hereafter LDK, 1985) model describes crop yield as a function of both salinity concentration and the "effective" volume of applied water, defined as the sum of irrigation and precipitation reduced by a rainfall effectiveness factor accounting for evaporation/runoff. The salinity of the applied water (S_{App}) is calculated as the weighted mean salinity of both the source water (S_{Source}) and precipitation (negligible salinity), consistent with the work of Meiri et al. (1986). The relationship for each crop type is fully specified with the input of the crop's water-salinity-yield characteristics, including salinity threshold, salinity/yield slope, water/yield slope, and ET_{max} (table 2). The notable feature of this model is that very high crop yields can be maintained even under conditions of elevated salinity if a sufficient volume of water is applied (figure 1).

The LDK model is used to modify base year irrigation demand in a manner similar, but not identical, to that described by Lee and Howitt (1996). Lee and Howitt modify marginal benefits under alternative salinity levels through the development of a "yield shift" function used to recompute demand based on quadratic fits of production data. The current study takes a slightly different approach. The LDK relationships (not reproduced here) describe the fractional yield decline ($Y_d \in [1,0]$) as a function of both applied water and applied water salinity concentration, such that for any given set of crop-specific inputs (table 2), $Y_d = f(q_{POU}, S_{App})$. If a constant salinity (S_{App}) is specified, yield decline becomes solely a function of applied water, whereby $Y_d^{S_{App}} = f(q_{POU})$. This relationship is integrated into a simple crop production function which is used to derive the value of marginal production (VMP), as represented by:

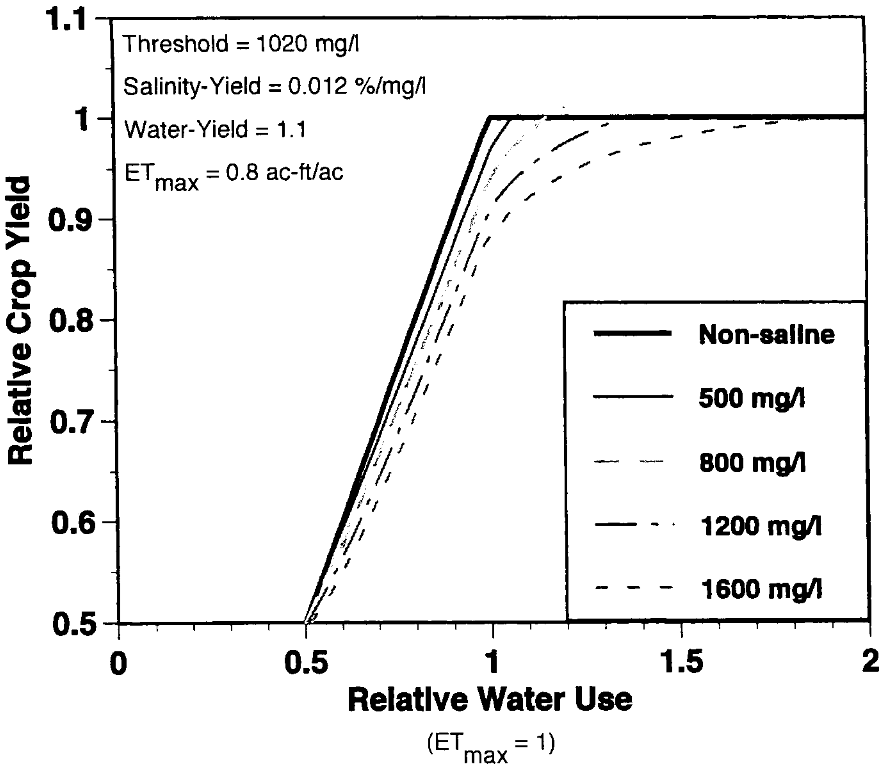


Figure 1. Effects of saline irrigation on vegetable yield

(6) $$VMP_{POU_{ij}}^{S_{App}}(\$/acre\text{-}foot) = \frac{Y_{Max_i} * \left[1 - Y_{d_i}^{S_{App}}\left(q_{POU_{ij}}\right)\right] * \left[P_i - C_{Var_{ij}}\right]}{q_{POU_{ij}}/\left(e_j/e_{B_j}\right)},$$

where Y_{Max_i} = maximum yield from crop type i (units/acre); P_i = price of crop type i ($/unit); and $C_{Var_{ij}}$ = nonwater variable costs for crop type i using technology j ($/acre).

The effects of base year salinity levels (S_{App}^{Base}) on crop yield are endogenized within base year demand functions (2), but water's value of marginal production will vary in a future year t as the salinity level changes (S_{App}^{t}). The ratio of base year VMP to that in year t is used to modify base year demand at the point of use. If real crop prices and nonwater variable costs remain constant, demand in year t becomes:

(7) $$MB_{POU_{ij}}^{Ag_t}(\$/acre\text{-}foot) = \frac{VMP_{POU_{ij}}^{S_{App}^{t}}}{VMP_{POU_{ij}}^{S_{App}^{Base}}} * \left[\frac{Q_{POU_{ij}}}{\alpha_i}\right]^{1/\varepsilon_i}$$

$$= \frac{\left[1 - Y_{d_i}^{S_{App}^{t}}\left(q_{POU_{ij}}\right)\right]}{\left[1 - Y_{d_i}^{S_{App}^{Base}}\left(q_{POU_{ij}}\right)\right]} * \left[\frac{Q_{POU_{ij}}}{\alpha_i}\right]^{1/\varepsilon_i}.$$

Point-of-use demand can then be translated to source water demand as described in (4), such that:

$$(8)\qquad MB^{Ag_t}_{Source_{ij}}(\$/acre\text{-}foot) = \frac{\left[1 - Y_{d_i}^{S^t_{App}}\left(q_{POU_{ij}}\right)\right]}{\left[1 - Y_{d_i}^{S^{Base}_{App}}\left(q_{POU_{ij}}\right)\right]} * \left[\frac{Q_{Source_{ij}} * (e_j/e_{B_j}) * \left[1 - L_i\right]}{\alpha_i}\right]^{1/\varepsilon_i} * (e_j/e_{B_j}) * \left[1 - L_i\right].$$

Agricultural benefits are computed by integrating (8) over Q_{Source}, although it should be noted that choke prices (P_{Choke}) are assumed for each crop's derived demand for water, such that annual benefits can be expressed as:

$$(9)\qquad Benefits^{Ag_t}_{Source_{ij}}(\$/year) = \left[Q_{Choke_{ij}} * P_{Choke_{ij}}\right] + \int_{Q_{Choke_{ij}}}^{Q_{Source_{ij}}} MB^{Ag}_{Source_{ij}}\, dQ_{Source}.$$

For the integration step in (9), the LDK relationships describing yield decline (Y_d) in (8) are relatively complex, and cannot be readily integrated via analytical methods. Therefore, the benefits of source water usage in (9) are computed numerically using an appropriate software package [e.g., *Mathematica* (Wolfram and Gray, 1996)].

It is important to point out that the LDK relationships describe crop yield as a function of a steady-state root zone salinity profile. This profile reflects the salt accumulation which would occur in the soil if the specified volume of water with a given salinity were applied over the long term. As a result, the historical effects of previous irrigation on soil salinity can be approximated in any individual period, provided that changes in the volume and salinity of applied water occur gradually, as is usually the case. This feature allows for the maintenance of a year-to-year continuity in soil-salinity conditions when considering a series of discrete time periods (as is done in this study).

Finally, it should be noted that this approach does not include consideration of factors related to soil drainage limitations (Knapp and Dinar, 1988) or water application/infiltration uniformity (Dinar, Letey, and Knapp, 1985; Feinerman, Knapp, and Letey, 1984; Letey, Vaux, and Feinerman, 1984; Feinerman and Yaron, 1983). Nonetheless, as reported in previous research, the use of average regional values (e.g., applied water, yield per acre) as inputs for irrigation production functions can often implicitly account for some uniformity effects at the regional level (Lee, 1992).

Measuring Water Use Costs

The costs of regional water use are described in three categories: total production costs of agricultural water, total production costs of municipal water, and municipal salinity damages. Note that while agricultural salinity damages are interpreted as a reduction in benefits, municipal damages accrue as an increase in costs, a logical choice given the assumption that salinity increases have a minimal impact on municipal demand. As findings are presented in terms of net benefits, this distinction has no effect on results.

Total production costs of agricultural water include the expense of acquiring and delivering raw water from source to field and the cost of applying it to a crop, neither of which is considered to be affected by salinity. Agricultural costs are represented as:

$$(10)\qquad Costs^{Ag}_{Source_{ij}}(\$/year) = C_{Acq_i}\left(Q_{Source_{ij}}\right) + \left[\left[F(t_{A_j}) * C^{Cap}_{A_j} * A_j\right] + \left[C^{O\&M}_{A_j} * Q_{POU_{ij}}\right]\right],$$

where $F(\cdot)$ = annual capital cost recovery function, $r[1+r]^{t_j}/([1+r]^{t_j}-1)$ (–); r = annual discount rate (–); t_A = expected life of irrigation technology (years); $C_{Acq}(\cdot)$ = function representing acquisition and delivery costs ($/acre-foot); C_A^{Cap} = capital costs of irrigation technology ($/acre); and $C_A^{O\&M}$ = operating and maintenance costs of irrigation technology ($/acre-foot).

The costs of municipal water production include source water acquisition/delivery, as well as treatment. In line with most observations of the water industry, all functions include both annualized capital and operating costs, whereby these relationships are representative of average costs (Griffin, 2001; American Water Works Association, 1991). Both conventional processes and membrane desalination are considered, as are combinations of the two which produce blended waters with variable salinity levels. An explicit development of the municipal water production cost function and the definitions of related parameters are described in ancillary work (see Characklis, 2004), but a general representation of these costs for any community i can be expressed as:

$$(11) \qquad C_{Source_i}^{Muni}(\$/Kgal) = C_{Acq_i}\left(Q_{Source_{ij}}\right) + \left[f_{d_i} * C_D\left(f_{d_i}, Q_{POU_i}, S_{Source}^t\right)\right] + \left[1 - f_{d_i}\right] * \left[C_C\left(f_{d_i}, Q_{POU_i}\right)\right],$$

where f_d = fraction to raw water treated via desalination (–); $C_D(\cdot)$ = function representing desalination costs ($/Kgal); and $C_C(\cdot)$ = function representing conventional treatment costs ($/Kgal).

Municipal production costs are described in standard industry units of dollars per thousand gallons ($/Kgal). Costs can be converted to $/acre-foot by simply multiplying (11) by 325.9 Kgal/acre-foot, and then converted to annual costs by multiplying the resulting value by annual production. This relationship (11) can be used to compute the cost of treatment via conventional processes alone (f_d = 0), via desalination alone (f_d = 1), or by a combination of both processes ($1 > f_d > 0$). The decision as to whether or not some level of desalination should be employed is governed by a comparison of desalination's additional costs with the reduction in municipal damages that would be realized by lowering treated water salinity levels.

Municipal damages are considered in three separate categories: accelerated degradation of equipment/appliances, accelerated degradation of infrastructure, and increased use of tap water substitutes (e.g., bottled water). Damages in each category are evaluated in the residential, commercial, industrial, and public sectors, then summed to provide a regional damage estimate. Again, category-specific relationships explicitly defining these damages, as well as the parameter values, are fully described in Characklis' (2004) ancillary work, and are not reproduced here. Nonetheless, general representations are presented below:

$$(12) \qquad Damages_{E\text{-}A_i}^{Muni}(\$/year) = \sum_{v=1}^{4}\sum_{u=1}^{y} f\left(S_{ds_i}^t, S_{Source}^t, N_{v_i}, n_{uv_i}, C_u, r\right),$$

$$(13) \qquad Damages_{Sub_i}^{Muni}(\$/year) = \sum_{v=1}^{4} f\left(N_{v_i}, C_{POU_v}, C_{DF_v}, S_{ds_i}^t, S_{Source}^t\right),$$

$$(14) \qquad Damages_{Infra_i}^{Muni}(\$/year) = \sum_{x=1}^{3} f\left(P_i, C_{PCC_x}, S_{ds_i}^t, S_{Source}^t, r\right),$$

where

u = index of equipment/appliance type, $u = 1, 2, ..., y$;
v = index of sector, with 1 = residential, 2 = commercial, 3 = industrial, and 4 = public;
x = index of infrastructure, with 1 = water treatment, 2 = distribution system, and 3 = wastewater;
$C_{u/POU/DF}$ = capital cost of equipment/appliance (u), point-of-use treatment device, or dispensed/filtered water, respectively (\$/unit);
C_{PCC} = per capita capital cost of infrastructure (\$/person);
N_v = number of connections serviced in sector v (–);
n_{uv} = number of item u per connection in sector v (units/connection);
P = population served by the water system (–); and
S_{ds} = salinity of desalinated water (mg/l).

Total regional municipal damages for each community type i are expressed as:

$$(15)\qquad Damages^{Muni}_{Total_i}(\$/year) = Damages^{Muni}_{E\text{-}A_i} + Damages^{Muni}_{Sub_i} + Damages^{Muni}_{Infra_i}.$$

The difference between the damages accruing when community i uses water with a salinity of S_{Source} (conventional processes don't lower salinity), and damages that accrue when treated water salinity is reduced to S_{ds} (desalination), is referred to as "mitigated damages." Mitigated damages are then compared with the additional costs of desalination such that, for any given values of S_{Source} and S_{ds}, community i will convert to desalination if:

$$(16)\qquad Damages^{Muni}_{Total_i}(S_{Source}) - Damages^{Muni}_{Total_i}(S_{ds_i}) > Costs^{Muni}_{Source_i}(1 \geq f_d > 0) - Costs^{Muni}_{Source_i}(f_d = 0).$$

Resolution of (16) requires knowledge of f_d, which specifies both the post-treatment salinity level (S_{ds}) and treatment costs. Previous analysis of the treatment decision (Characklis, 2004) reveals that the economies of scale associated with the individual treatment processes lead to corner solutions. Consequently, it is less expensive to convert entirely to desalination than it is to use a combination of smaller conventional and desalination processes. With f_d restricted to only two values, the independent variable in (16) becomes the source water salinity concentration (S_{Source}), such that when salinity rises to a level at which (16) becomes true, a community converts completely to desalination. Thus, each community has a binary choice with respect to treatment technology—either conventional processes ($j = 1$), or desalination ($j = 2$)—resulting in the addition of a second sub-subscript to the terms in (16), e.g., $Costs^{Muni}_{Source_i}(1 \geq f_d > 0) \Rightarrow Costs^{Muni}_{Source_{i2}}$.

The rule described in (16) will lead to decisions which maximize a municipality's net benefits for any given source water salinity concentration, as represented by:

$$(17)\qquad NB^{Muni}_{Source_{ij}}(\$/year) = Benefits^{Muni}_{Source_{ij}} - \left[Costs^{Muni}_{Source_{ij}} + Damages^{Muni}_{Total_{ij}}\right].$$

Calculating the Net Benefits of Salinity Management

The annual net benefits of regional water use in any year t with a particular source water salinity (S^t_{Source}) are defined as the difference between the sum of total benefits [(5), (9)] and the sum of total costs/damages [(10), (11), (12), (13), (14)] across all activities ($i = 1, 2, ..., m$):

$$(18) \quad NetBenefits^{S^t_{Source}}_{Regional}(\$/year) = \left[\sum_{i=1}^{n} Benefits^{Muni_t}_{Source_{ij}} + \sum_{i=n+1}^{m} Benefits^{Ag_t}_{Source_{ij}}\right] - \left[\sum_{i=1}^{n} Costs^{Muni_t}_{Source_{ij}} + \sum_{i=n+1}^{m} Costs^{Ag_t}_{Source_{ij}} + \sum_{i=1}^{n} Damages^{Muni_t}_{Total_{ij}}\right].$$

The change in annual net benefits accruing as a result of a salinity management program are therefore equal to the difference between (18) calculated at two different salinity levels, one with the program in place ($S^{t_1}_{Source}$) and the other without ($S^{t_2}_{Source}$).

This general approach can be applied in many areas with knowledge of region-specific parameters. But in order to calculate the benefits accruing over multiple years, future scenarios must be specified for the region of interest, including trends in population, water use patterns, and salinity levels. In some situations there also may be important feedback effects on downgradient salinity due to water allocation decisions. However, in many watersheds return flow does not reenter the studied water body. For example, water use in coastal regions may result in seaward return flow (as in the case study conducted here) or surface water conveyances may transport water far from the original source. Examples here include regions served by the Colorado Aqueduct (e.g., Los Angeles, San Diego, Imperial, and Coachella irrigation districts) and Central Arizona Project (e.g., Phoenix, Tucson, and several irrigation districts), all of which are some distance from their primary water source. Similar scenarios may also arise as Las Vegas taps Lake Mead, or if Dallas-Ft. Worth should begin to divert water from the Red River.

The Study Region

The Lower Rio Grande Valley is similar to many other western regions facing rising salinity in that it contains both an established agricultural community and an expanding urban population. The Valley consists of four counties (Cameron, Hidalgo, Starr, and Willacy) supporting around 400,000 acres of irrigated farmland (Texas Agricultural Statistics Service, 2000), and a rapidly growing population now approaching one million (U.S. Department of Commerce, 2000). Regional water use is dominated by the agricultural sector (85% agricultural, 14% municipal, and 1% industrial), but this pattern is changing as a result of urban growth that is projected to raise regional population to around 2 million by the year 2040 (Texas Water Development Board, 1996a). The Rio Grande provides over 98% of regional water supply, with flows regulated by two upstream reservoirs, Amistad and Falcon. Reservoir releases (excluding flood control) have historically varied between 850,000 and 1,230,000 acre-feet per year (International Boundary and Water Commission, 2002), with the latter amount sufficient to satiate regional water demand even during dry years. Average salinity concentrations in the

Rio Grande have climbed from approximately 500 mg/l in the late 1960s to over 900 mg/l in recent years (Miyamoto, Fenn, and Swietlik, 1995). Concerns over rising salinity have been sufficiently serious that state and federal agencies have begun discussing salinity management options for those upstream reaches acting as primary salt contributors. The nature of any potential management program currently remains vague, but the issue will take on greater significance as salinity levels continue to rise.

The base year for this analysis is set in 1995, a year in which the average salinity in the Rio Grande measured approximately 900 mg/l, all municipal treatment was performed via conventional processes, and virtually all irrigation involved simple flood techniques. These conditions are endogenized within base year demand functions (2) which are developed for seven different activities in the Valley—two municipal ($i = 1, 2$) and five agricultural ($i = 3, 4, ..., 7$)—using the parameters reported in table 1. A distinction is made between large and small municipalities based on differences in the size and cost of water treatment facilities serving the two communities, as well as some differences in the distribution of water use (i.e., residential vs. commercial vs. industrial).

The municipal treatment technologies considered include conventional treatment and membrane desalination ($j = 1, 2$). Parameters used in the specification of capital and operating costs for municipal treatment technologies are fully described elsewhere (Characklis, 2004). This work also defines the relationships and parameter values used in calculating municipal salinity damages, including those for five different equipment/appliance items ($y = 5$): water heaters, faucet fixtures, dish washers, clothes washers, and garbage disposal units. Alternative irrigation technologies include flood, surge, sprinkler, low-energy precision application (LEPA), and drip ($j = 3, 4, ..., 7$), and the capital and operating costs for these technologies are drawn from available literature (Hooker and Alexander, 1998; Letey et al., 1990). Water acquisition and delivery in the Valley is generally performed by irrigation districts that charge an average of $16 per acre-foot to deliver water from the river to both municipal and agricultural users. Further additions are made to these costs to account for scarcity-induced increases in the price of source water [shadow prices derived from equation (19)].

Agricultural activities are grouped into the five classifications based on per acre water use and salt sensitivity: citrus (oranges, grapefruit), sugar cane, vegetables (cabbage, lettuce, melons, onions, peppers, tomatoes), corn, and field crops (cotton, grain sorghum). As salinity has increased, the salt-sensitive citrus and vegetable crops have seen considerable increases in water application relative to salt-tolerant crops (table 2), while irrigation methods remained essentially unchanged (Texas Agricultural Extension Service, 1972–73, 1990–96; Texas Water Development Board, 1996b). Thus far, irrigators appear to have chosen to combat rising salinity by increasing irrigation rates for sensitive crops rather than altering the crop mix, as regional records show little temporal long-term variation in Valley cropping patterns (Texas Agricultural Statistics Service, 2000). As current irrigation practices seem capable of mitigating most adverse salinity impacts even at concentrations that will not be reached for many years (see the discussion of "Agriculture" in the Results section below), this seems unlikely to change anytime soon.

Seven base year demand functions are initially specified, but consideration of all of the potential technologies expands this number of functions to 29 (5 crop types × 5 irrigation technologies; 2 municipal sizes × 2 treatment technologies), resulting in 12,500 possible activity-technology combinations (i.e., $5^5 \times 2^2$). On closer examination, however, this number can be significantly reduced because a number of crop-technology pairings are deemed unrealistic (e.g., LEPA on citrus) or economically impractical. This lowers the total number of crop-technology combinations considered from 3,125 to 144, and the total number of regional combinations (including municipal) to 576.

Once the base year demand and cost functions are specified for each activity and technology, region-specific trends related to salinity, population, and water use patterns need to be defined for the Valley. No detailed hydrologic models of the Lower Rio Grande have yet been constructed, so the historical average rate of salinity increase (15 mg/l/year) is extrapolated into the future to project the concentrations which would occur in the absence of salinity management. The absence of detailed hydrologic modeling also results in the assumption of a hypothetical salinity management program, one that maintains salinity in the Rio Grande at a constant level of 900 mg/l over time.

Municipal demand functions are expanded outward in future years, driven by population growth (Texas Water Development Board, 1996a) and an assumption of constant per capita water use. This growth also impacts water use patterns, as a correlation has been observed between increasing population and reductions in irrigated acreage, with 2,300 irrigated acres being removed from production for each increase of 10,000 people (Lower Rio Grande Development Council, 1999). Most of the converted farmland lies in close proximity to municipalities, suggesting a primary role is played by urban expansion in determining which land is taken out of production. As location, not crop type, appears to be the dominant factor, acreage reductions are distributed across all crop types on a pro rata basis, and agricultural demand functions in later years are contracted to correspond with these reductions. This decline in local agricultural production could raise the price of some farm products, creating a feedback wherein farmers respond by increasing planting and raising irrigation water demand. However, crop production in the Valley is not considered significant at the national level; this is particularly true of the low-valued field crops (e.g., cotton) that dominate local acreage. Thus, regional acreage shifts are assumed to have a minimal impact on market prices at the national or state levels, and a negligible impact on water demand.

With respect to determining technology choices and water allocation patterns in future years, decisions are made on the basis of maximizing regional net benefits. In many regions it might be sensible to simply assume water allocation and technology selection (particularly in agriculture) remain relatively constant over time. However, in the Valley an assumption of efficient behavior seems reasonable given the prevailing institutional circumstances. The Valley supports a system of robust water marketing institutions that have traditionally resulted in the type of price signals which drive efficient water choices (Griffin and Characklis, 2002). An examination of current technology choices in the Valley suggests, in terms of efficiency, agricultural water users are currently employing optimal, or nearly optimal, technologies (Lower Rio Grande Development Council, 1999). These market institutions have also given rise to efficient water allocation across municipal and agricultural activities (Chang and Griffin, 1992; Characklis, Griffin, and Bedient, 1999), indicating that irrigators have adjusted their behavior to coincide with changing water demand in the region.

Determining the efficient technologies and allocations in any future year t begins by using the established trends for salinity, population, and irrigated acreage to describe regional conditions in that year. The benefit, cost, and damage functions for year t then become fully specified once a technology for each activity is selected. The resulting activity-technology combination (one of the aforementioned 576 possibilities) allows regional net benefits [equation (18)] to be explicitly defined as a function of each activity's source water allocation ($Q_{Source_{ij}}$). Water allocation in year t is then determined by the distribution that maximizes net benefits relative to a regional supply constraint, mathematically represented as:

$$\text{(19)} \qquad \underset{Q_{Source_{ij}}}{\text{Maximize}}\ \mathit{NetBenefits}_{Regional}^{S^t_{Source}}$$

$$\text{s.t.:} \sum_{i=1}^{7} Q_{Source_{ij}} \leq \bar{Q}_{Source},$$

where $\bar{Q}_{Source}$ = annual source water supply, acre-feet/year; $\bar{Q}_{Source} \in [850{,}000, 1{,}230{,}000]$). This step is conducted for all 576 activity-technology combinations in each year, with the combination yielding the highest net benefits prevailing in that year. This process of computing net benefits is repeated for all years of interest under both the "with" and "without" management scenarios until a schedule of annual values has been developed for both scenarios.

Interest in the relative ordering of the combinations makes enumeration preferable to more efficient, but opaque, maximization methods. The modest number of combinations considered keeps computation times quite brief, but if the number of combinations were significantly larger, the described approach could be modified to fit within many available optimization packages (e.g., GAMS). Equation (19) could also be modified to suit other region-specific situations as well. If, for example, salinity increases were determined to significantly influence crop choices, the net benefits function might be modified to consider changes in the distribution of irrigated acreage.

It is also important to note that although predictions of future conditions are made on the basis of a series of static annual evaluations, the nature of the changes occurring within the region allow for a reasonably continuous approximation of the evolution of regional water use in the Valley. The trends that impact technology and water use choices (i.e., salinity, population, irrigated acreage) are continuously positive or negative, so there is no concern over back-tracking (i.e., switching to a new technology in one year, and back to the old technology the next year). In addition, because these trends are sufficiently gradual, there also is no concern over multiple technology changes over short time periods (e.g., switching to surge irrigation, a five-year investment, and then switching to LEPA two years later).

Results

In order to better identify important drivers of the findings, results are presented in three parts. The first two sections describe the isolated impacts of rising salinity on the municipal and agricultural sectors, respectively, without consideration of temporal changes in population or water use. The third section considers both sectors simultaneously within a multi-year analysis incorporating changes in salinity, technology, population, and water use patterns. Results are described over the years 1995 to 2040, with salinity rising from 900 to 1,600 mg/l over that period. All cost and benefit values are presented in 2002 dollars.

Municipal

Treatment plant sizes are established based on typical facilities operating in the region (U.S. Bureau of Reclamation, 1995), with small municipalities served by 3 million gallon per day (MGD) facilities, and large municipalities served by 12 MGD facilities. In the case of small municipalities, increases in salinity damages exceed the additional costs of desalination [see equation (16)] when source water salinity rises above a threshold concentration of 1,195 mg/l (figure 2). Desalination does not become economically preferable for large municipalities until salinity exceeds 1,655 mg/l (a level which does not occur until 2044). Differences in the threshold concentrations are due to different distributions of water use within the different municipal types. Residential water use accounts for the majority of municipal damages in both, but the large municipalities have a smaller fraction of residential connections (Characklis, 2004). The large municipalities also have higher residential usage rates, which lowers the volumetric damage rate ($/Kgal) relative to smaller communities.

The conversion of small municipalities to desalination is accompanied by increases in both source water demand and source water consumption. This leads to a step increase in the net benefits of municipal water use. Notice that the parenthetical sum of costs and damages in (17) is equal at the threshold salinity (16) regardless of which technology is employed, and this sum increases (or decreases) in a continuous manner as the city switches between technologies. Benefits, on the other hand, increase instantaneously with the implementation of desalination as a result of the increased demand for source water. The increase in source water consumption will not be quite as large as might be expected given the relative differences in technology efficiency, because increased tap prices for desalinated water reduce consumption at the tap to some degree. Nonetheless, the net effect is still increased use and a corresponding increase in both benefits and net benefits for the small municipalities.

Agriculture

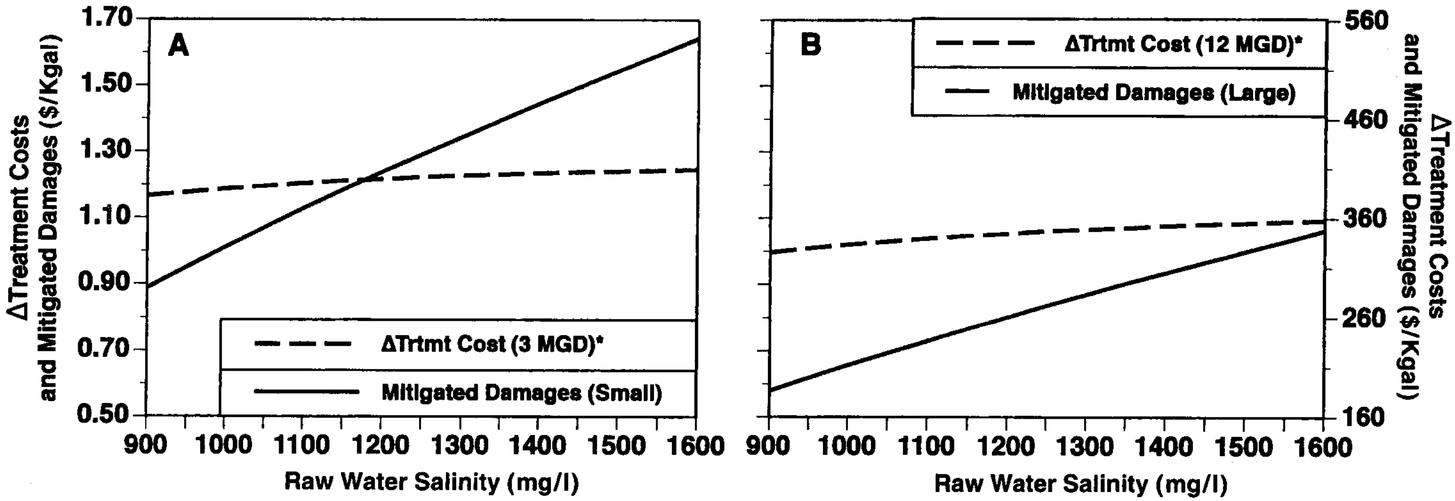
The agricultural activity-technology combination that yields maximum net benefits in all years is the combination which employs surge techniques on water-intensive citrus and sugar cane, and flood techniques on vegetables, corn, and field crops. Currently in the Valley, flood irrigation is used on all crops (Texas Water Development Board, 1996b), a scenario that yields the second highest level of net benefits in all years. All other combinations generate net benefits at a significantly lower rate than these two, even with variations in salinity level and available water supply. These results are consistent with the guidance of regional advisory groups who have recommended surge irrigation as a more efficient alternative for water-intensive crops (Lower Rio Grande Development Council, 1999; Fipps, 1998). Agreement among these results, current practice, and advisory recommendations suggests that the model is reasonably representative of agricultural activities.

Results representing the net benefit-maximizing technology combination are presented for three different salinity levels (table 3) when water supply is not limiting and without consideration of changes in population or water use. Net benefits are reduced as salinity increases, with the salt-tolerant field crops experiencing the smallest relative decline (5%), and corn the largest (18%). While both vegetables and citrus crops are more

Table 3. Agricultural Impacts of Rising Salinity When All Other Regional Conditions Remain Constant at Base Year (1995) Levels

	Crop / (Irrigation Technology)											
	Field Crops / (Flood)		Corn / (Flood)		Vegetables / (Flood)		Sugar Cane / (Surge)		Citrus / (Surge)		Total	
Salinity Level	NB ($MM)	Acre-Feet (× 10^3)	NB ($MM)	Acre-Feet (× 10^3)	NB ($MM)	Acre-Feet (× 10^3)	NB ($MM)	Acre-Feet (× 10^3)	NB ($MM)	Acre-Feet (× 10^3)	NB ($MM)	Acre-Feet (× 10^3)
900 mg/l	8.5	458.8	1.7	88.8	26.0	161.5	3.5	181.1	19.8	120.2	59.5	1,011
1,300 mg/l	8.4	452.5	1.5	84.8	25.2	161.5	3.3	177.6	19.0	115.7	57.4	992
1,600 mg/l	8.1	447.3	1.4	82.0	24.5	161.5	3.1	175.1	18.4	112.5	55.5	979

Note: NB = net benefits.



* Desalination facility configured to produce treated water with 200 mg/l total dissolved solids.

Figure 2. Mitigated damages and increased treatment costs arising from desalination for (A) small municipality with a 3 MGD plant, and (B) large municipality with a 12 MGD plant

sensitive to elevated salinity levels than corn, both receive water applications well in excess of evapotranspiration (ET) requirements (table 2), providing some level of protection against salinity's adverse effects. In contrast, corn, which is grown primarily for livestock feed, receives the lowest relative amount of base year irrigation ($0.8 \times ET_{max}$). The efficient level of water use in several irrigated activities declines as the marginal value of the increasingly saline irrigation water declines and the cost of delivery and application remains constant. The marginal productivity of irrigating corn is most affected by elevated salinity, leading to the largest reduction in allocation. With respect to the more highly valued crops, the current (generous) irrigation rates appear sufficient to maintain productivity near current levels even as salinity rises to 1,600 mg/l.

The reductions in agricultural net benefits computed using the described approach are relatively small, $2.1 million annually as salinity rises from 900 mg/l ($59.5 million) to 1,300 mg/l ($57.4 million), and $4 million as salinity increases further to 1,600 mg/l. These reductions are of the same order as those calculated in other studies using nonlinear agronomic relationships and empirical irrigation rates (Lee and Howitt, 1996; Gardner and Young, 1985), but substantially different than those making use of linear models with water levels fixed at ET_{max} (Bookman-Edmonston Engineering, Inc., 1999; Lohman et al., 1988; Anderson and Kleinman, 1978). For comparative purposes, the "linear-fixed" approach produces a regional reduction in net benefits of $13.3 million as salinity rises from 900 mg/l to 1,300 mg/l, and $26.1 million as salinity increases to 1,600 mg/l.

Regional Multi-Year

Results from regional multi-year analyses are described with consideration of projected changes in salinity, population, and land use (table 4). Calculations of net benefits and water use are made for the "with" and "without" management scenarios under varying levels of regional water supply. For the large municipalities, the benefits of salinity management rise over time as their water demand grows and the difference between salinity levels in the "with" and "without" scenarios increases. Reductions in regional water supply have little impact on either municipal net benefits or municipal allocation, as agriculture bears most of the burden in water-scarce years. Similar results are generated for the small municipalities if the possibility of desalination is not considered (see parenthetical values in table 4). If desalination is considered, however, different results emerge.

Without management, salinity levels rise above the 1,195 mg/l threshold concentration in 2013, and small communities convert to desalination. This conversion brings about an instantaneous increase in source water demand and consumption, leading to higher net benefits accruing to the small municipalities [see equation (17)]. The source of this additional municipal water is agriculture, and the resulting increase in net benefits from this transfer indicates that this water is more beneficial in lowering municipal salinity damages than it is in agricultural production. In subsequent years (e.g., 2021 and 2040), the net benefits in the "without" scenario, which include desalination, are sufficiently high that the management program actually provides a lower level of net benefits to smaller communities (hence, negative benefits for management).

It should be noted this result is somewhat dependent on the salinity level achieved through the management program. If the program were able to reduce source water

Table 4. Annual Net Benefits and Water Allocation for Representative Years Under Varying Water Supply Levels

		1995 (base year)		2021[a]					
		Base Year Salinity = 900 mg/l		Salinity = 900 mg/l (w/salinity mgmt)		Salinity = 1,300 mg/l (w/o salinity mgmt)		Difference (benefits of management)	
Description	Annual Supply (Ac-Ft × 10³)	Net Benefits ($MM)	Acre-Feet (× 10³)	Net Benefits ($MM)	Acre-Feet (× 10³)	Net Benefits ($MM)	Acre-Feet (× 10³)	Net Benefits ($MM)	Acre-Feet (× 10³)
Large Municipal	1,230	206.0	106.5	210.9	194.8	196.5	194.8	+14.4	0.0
	1,000	205.5	106.2	210.9	194.8	196.5	194.8	+14.4	0.0
	850	204.8	105.7	210.4	194.5	196.0	194.5	+14.4	0.0
Population (× 10³):		532		973					
Small Municipal[b]	1,230	102.2	38.9	104.0	71.1	105.8	74.1	-1.8	-3.0
						(98.1)	(71.1)	(+5.9)	(0.0)
	1,000	102.0	38.8	104.0	71.1	105.8	74.1	-1.8	-3.0
						(98.1)	(71.1)	(+5.9)	(0.0)
	850	101.7	38.5	103.8	71.0	105.6	74.0	-1.8	-3.0
						(97.9)	(71.0)	(+5.9)	(0.0)
Population (× 10³):		227		415					
Agricultural	1,230	59.5	1,011	38.7	652.1	37.1	640.1	+1.6	+12.0
	1,000	55.9	855	38.7	652.1	37.1	640.1	+1.6	+12.0
	850	50.5	706	35.1	584.4	33.9	581.4	+1.2	+3.0
Irrigated Acres (× 10³):		408		289					
Regional Totals	1,230	367.7	1,156	353.6	918	339.4	909	+14.2	+9
	1,000	363.4	1,000	353.6	918	339.4	909	+14.2	+9
	850	357.0	850	349.3	850	335.5	850	+13.8	0

[a] Desalination is the economically efficient treatment choice for small municipalities, i.e., source water salinity > 1,195 mg/l.
[b] Values in parentheses are results when desalination is not considered.

salinity to 300 mg/l, the reduction in salinity damages in the "with" scenario might be sufficiently large to outweigh the increase in benefits that occurs with desalination implementation in the "without" scenario, thus leading to positive benefits for the program. However, reduction to any level close to 300 mg/l is not very realistic given that regional management programs are rarely capable of doing more than maintaining or slightly reducing salinity levels, and are seldom even considered until salinity reaches 700 to 800 mg/l (Lee and Howitt, 1996; Gardner and Young, 1988). Thus, in general, regions considering salinity management may need to contemplate the possibility that some users (under some circumstances) might be better off without management.

The annual net benefits accruing to agricultural water use decline significantly over time, but this is primarily due to reductions in irrigated acreage, not rising salinity. Comparing results from both scenarios reveals the loss of agricultural net benefits attributable to increasing salinity is relatively modest, as are the benefits agriculture

Table 4. Extended

		2040[a]					
		Salinity = 900 mg/l (w/salinity mgmt)		Salinity = 1,300 mg/l (w/o salinity mgmt)		Difference (benefits of management)	
Description	Annual Supply (Ac-Ft × 10³)	Net Benefits ($MM)	Acre-Feet (× 10³)	Net Benefits ($MM)	Acre-Feet (× 10³)	Net Benefits ($MM)	Acre-Feet (× 10³)
Large Municipal	1,230	214.7	262.8	182.3	262.8	+32.4	0.0
	1,000	214.7	262.8	182.3	262.8	+32.4	0.0
	850	214.7	262.8	182.3	262.8	+32.4	0.0
Population (× 10³):		1,312					
Small Municipal[b]	1,230	105.4	96.0	113.0 (92.2)	100.6 (96.0)	-7.6 (+13.2)	-4.6 (0.0)
	1,000	105.4	96.0	113.0 (92.2)	100.6 (96.0)	-7.6 (+13.2)	-4.6 (0.0)
	850	105.4	96.0	113.0 (92.2)	100.6 (96.0)	-7.6 (+13.2)	-4.6 (0.0)
Population (× 10³):		560					
Agricultural	1,230	22.3	376.2	20.8	364.2	+1.5	+12.0
	1,000	22.3	376.2	20.8	364.2	+1.5	+12.0
	850	22.3	376.2	20.8	364.2	+1.5	+12.0
Irrigated Acres (× 10³):		199					
Regional Totals	1,230	342.4	735	316.1	728	+26.4	+7
	1,000	342.4	735	316.1	728	+26.3	+7
	850	342.4	735	316.1	728	+26.3	+7

would realize as a result of salinity management. Similarly, rising salinity plays only a small role in reducing agricultural water allocation over time, a trend which is instead largely due to the conversion of irrigated land to urban activities. In future years, the resulting decline in regional water demand means that reducing supply (i.e., 850,000 acre-feet/year) has a relatively small effect on regional net benefits.

The differences in annual net benefits between the "with" and "without" scenarios are equivalent to the benefits of salinity management. Figure 3.1 presents these values for both agricultural and municipal users over the years 1995 to 2040. Municipal losses grow rapidly from 1995 to 2013, but the rate of increase declines following the implementation of desalination in the small communities (i.e., from 2014 onward). Agricultural losses increase for a time, but eventually plateau and then begin to decline as irrigated acreage is removed from production.

The information in figure 3.1 is used to evaluate the present value benefits for the hypothetical salinity management program. If the program were implemented upstream in 2005, it is likely, given typical flows and reservoir storage levels, to take at least two

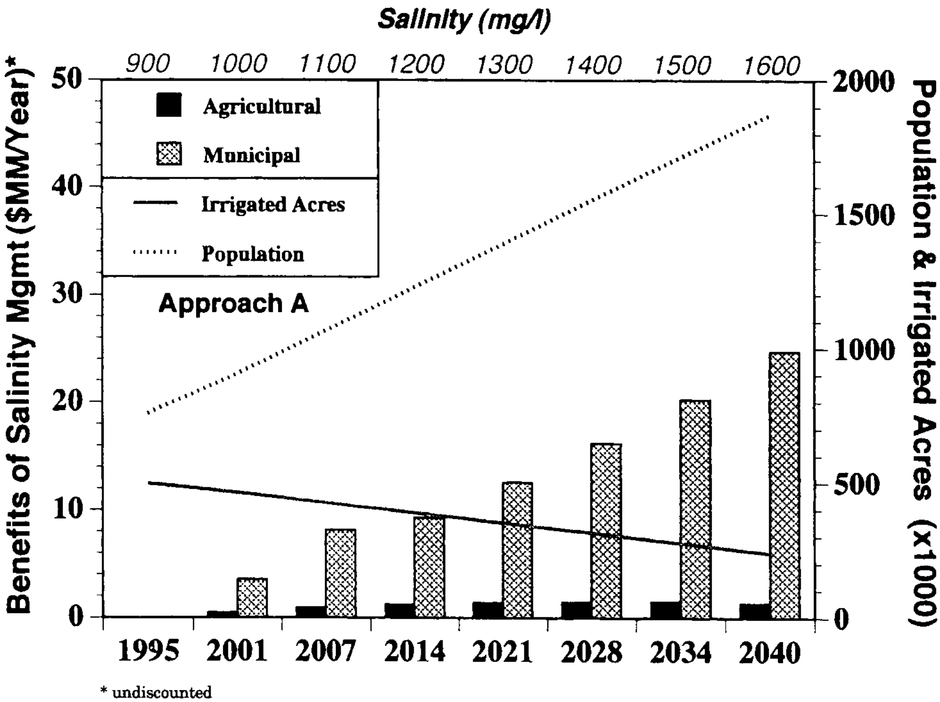


Figure 3.1. Estimates of the annual benefits of salinity management using approach A (PVB_A = $176 mil.)

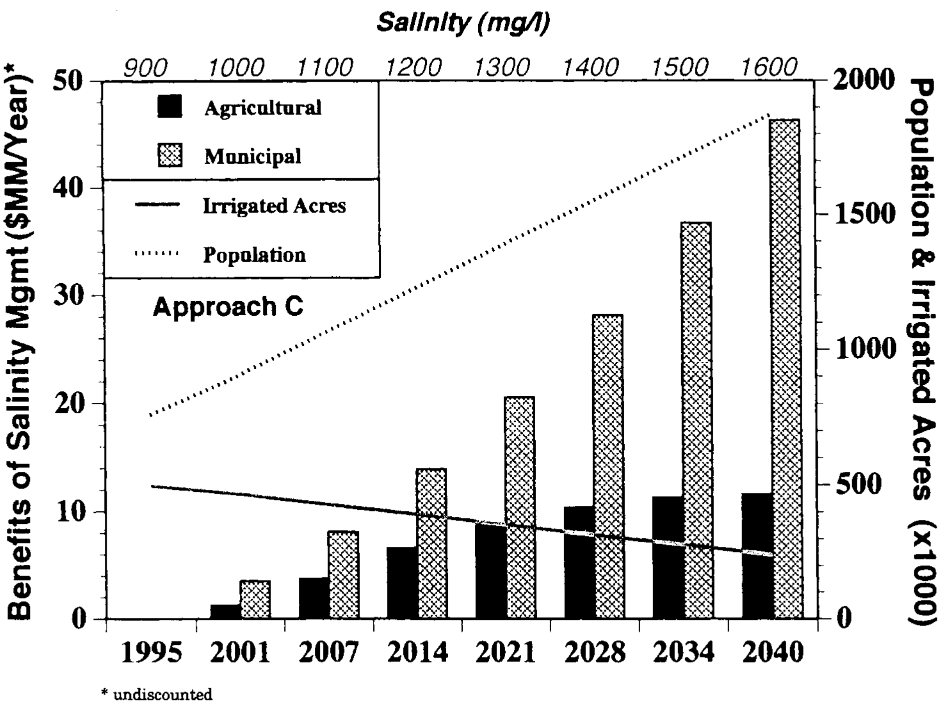


Figure 3.2. Estimates of the annual benefits of salinity management using approach C (PVB_C = $277 mil.)

years before the full effects of any reduction are felt downstream in the Valley. If a reduction to 900 mg/l is assumed to take place instantaneously at the beginning of 2007, regional benefits would begin to accrue at a rate of $9.1 million per year and increase in subsequent years. Over a 30-year management program life, using a discount rate of 6%, present value benefits at the time of implementation (2005) would be $168.7 million, with $159.5 million accruing to the municipal sector. This value assumes a water supply sufficient to satiate regional demand in all years. An expected value for program benefits could also be calculated based on ensembles of randomly generated supply values; but given the relatively small differences in net benefits observed under reduced supply conditions (table 4), estimated values would not change substantially.

Comparative Analysis

The effect of methodological choices on the calculation of a program's present value benefits (PVBs) can perhaps best be illustrated by comparing estimates in terms of the differences that arise from (*a*) consideration of desalination for municipal users, (*b*) the generalized approach used for calculating agricultural damages, and (*c*) incremental versus step changes in salinity and water use patterns. Six different variations of the PVB calculations in the Valley are presented, with the same temporal trends in population growth and water use patterns used in each to facilitate comparisons (table 5).

Approach A corresponds to the methodology described in this work. A comparison of the PVBs generated by approaches A (PVB_A = $176 million) and B ($PVB_B$ = $217 million) indicates that including consideration of desalination can reduce the estimates of municipal benefits by over 20%. Comparison of results from approaches B and C (PVB_C = $277 million) demonstrates that use of the "nonlinear agro-econ" relationships with empirical inputs for irrigation rates can substantially reduce agricultural benefit estimates relative to the more rigid "linear" relationships. An annual comparison of the differences in municipal and agricultural benefits when desalination and nonlinear agro-econ methods are considered (as opposed to no desalination and linear agronomic models) can be observed by comparing results from approaches A (figure 3.1) and C (figure 3.2) over time.

Some previous studies have used methods falling somewhere between approaches B and E (PVB_E = $361 million), calculating damages based on a single average salinity value, and in some cases more than one water use pattern—but no studies have used a continuum of values for either parameter. A comparison of approaches B and E reveals considerable differences in regional benefits estimates when calculations are based on "incremental," as opposed to "step-average," changes in salinity levels and water allocation patterns. Assigning the step-average benefit values to all years leads to significant overestimates of discounted benefits in the early years relative to the incremental approach in which benefits in earlier years are much lower. An even greater distorting effect can be imposed by evaluating benefits on the basis of a single "step" change in salinity and water use patterns, in which conditions existing in the last year of program life are taken as representative of all years. A comparison of present value benefit totals computed with consideration of incremental changes (approach C) and those assuming a step change (approach F) indicate this choice can lead to benefit estimates that differ by a factor greater than two (PVB_C = $277 million; PVB_F = $703 million). The benefit estimation methods used in several Bureau of Reclamation-sponsored studies are similar to those used in approach F.

Table 5. Comparison of Approaches to Calculating the Benefits of Salinity Reduction

Features	Approach A	Approach B	Approach C	Approach D	Approach E	Approach F
Change in salinity and water use	Incremental [a]	Incremental	Incremental	Step-Average [b]	Step-Average	Step [c]
Desalination an option?	Yes	No	No	Yes	No	No
Basis for crop-salinity model	Nonlinear Agro-Econ [d]	Nonlinear Agro-Econ	Linear Agro [e]	Nonlinear Agro-Econ	Nonlinear Agro-Econ	Linear Agro
Benefits Category	**Present Value Benefits** [f] ($MM)	**Present Value Benefits** ($MM)	**Present Value Benefits** ($MM)	**Present Value Benefits** ($MM)	**Present Value Benefits** ($MM)	**Present Value Benefits** ($MM)
Municipal	159.5	199.8	199.8	207.4	339.6	536.1
Agricultural	16.9	16.9	77.4	21.0	21.0	167.2
Regional Total	176.4	216.7	277.2	228.4	360.6	703.3

[a] Incremental: The difference in annual net benefits is evaluated in each year based on current salinity and water allocation pattern, with total benefits of the management program equal to the discounted sum of these annual values over its lifespan.

[b] Step-Average: The difference in annual net benefits is determined for the mid-point year in the program lifespan. This value is substituted for all years, with total benefits of the management program equal to the discounted sum of these values over its life.

[c] Step: The difference in annual net benefits is determined for the last year of the program's lifespan. This value is substituted for all years, with total benefits of the management program equal to the discounted sum of these values over its life.

[d] Nonlinear Agro-Econ: Agricultural losses are calculated on the basis of nonlinear agronomic-economic relationships involving empirical applied water levels, as described in this work and similar to methods used by Lee and Howitt (1996).

[e] Linear Agro: Agricultural losses are calculated on the basis of linear agronomic relationships assuming applied water levels are fixed at ET_{max}.

[f] Present value benefits are relative to the time of program implementation (2005), and assuming water supply > 1,230,000 acre-feet/year in all years.

While direct comparisons of benefit estimates obtained from different river basins would be inappropriate, a general comparison of the results of this study (approach A) with those from other regional studies provides useful insights (all comparisons in $2002). The average annual benefits associated with reducing salinity from 1,100 mg/l to 800 mg/l in the Colorado River have been valued at approximately $48 per ton (Gardner and Young, 1985), while an estimate generated for the same basin by the U.S. Bureau of Reclamation (1983) was $96 per ton. The annual benefit of salt removal computed in this work is not a single value, but rather a range extending from $21 to $30 per ton, depending on the year.

In order to be useful, program benefits need to be compared against a management program's costs. The costs of salinity management in the Rio Grande have not been estimated, but values have been estimated for other basins. For 8 of the 11 projects considered in the Colorado River salinity management program, costs exceeded $113 per ton of salt removed; the remaining three ranged between $19 and $104 per ton (Gardner and Young, 1985). If management costs in the Rio Grande are similar, few management projects would be approved on the basis of a benefit-cost ratio criterion. As a point of comparison, the cost of salt removal via desalination varies from approximately $200 to $400 per ton, depending on treatment plant size and raw water salinity. In this case, however, the expenditure is targeted only toward municipal users who suffer the majority of adverse impacts.

Conclusions

When evaluating the regional benefits of salinity reduction, consideration of desalination, as well as the incremental nature of salinity increases and shifting water use patterns, can have a significant impact. These results demonstrate that salinity control benefits can be substantially overestimated if such factors are not integrated within the analysis. This finding is likely to hold true even as more advanced methods of damage estimation are developed for specific agricultural or municipal activities. In addition, sizeable differences in the damages accruing within the municipal and agricultural sectors also provide an indication of where future research efforts to improve damage estimates might be most productively directed. While the use of more detailed agronomic models could provide more accurate agricultural damage estimates, the differences are likely to be small at the regional scale and play a correspondingly reduced role in decision making. Efforts to sharpen the methods used to estimate municipal damages, on the other hand, would likely have a much greater impact on future cost-benefit analyses.

The need for more accurate methods of evaluating salinity management benefits is increasing as the number of regions facing rising salinity continues to grow. Programs designed to mitigate these increases are expensive and should continue to be subjected to detailed cost-benefit analysis prior to implementation. The findings of this work should provide information that will assist in more complete evaluations.

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