IMPROVED ESTIMATES OF ECONOMIC DAMAGES FROM RESIDENTIAL USE OF MINERALIZED WATER

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Guy E. Ragan, Carole Makela, and Robert A. Young

Colorado Water Resources Research Institute

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Guy E. Ragan, Carole J. Makela, and Robert A. Young

Departments of Agricultural and Resource Economics and Design,
Merchandising, and Consumer Sciences
Colorado State University

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COLORADO WATER RESOURCES RESEARCH INSTITUTE
Colorado State University
Fort Collins, Colorado 80523-0002

Robert C. Ward, Director

FOREWORD

The contents of this report were developed under a grant from the Department of Interior, U.S. Geological Survey. However, those contents do not represent the policy of that agency and the reader should not assume endorsement by the Federal Government.

This research was supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 14-08-0001-G1984. Support was also provided by the Colorado State University Agricultural Experiment Station. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the views of Colorado State University.

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ABSTRACT

IMPROVED ESTIMATES OF ECONOMIC DAMAGES FROM RESIDENTIAL USE OF MINERALIZED WATER

Salinity (dissolved mineral constituents), which occurs naturally in both surface and groundwater, has been identified as a source of reduced effectiveness and lowered service lives of household appliances in many areas of the United States. This study statistically analyzed newly collected mail survey data obtained from the Arkansas River basin in Southeastern Colorado. We collected information on types and ages of water-using appliances owned and age at failure of previously owned appliances from 872 households. The random sample of households was selected from communities experiencing water qualities ranging from about 100 milligrams per liter in the mountain headwaters to 3500 mg/l in the eastern plains. From a separate survey of all identifiable plumbers and appliance repairers in the region, 39 returns were received. The household survey was judged to provide the more suitable data base, both because of more complete and accurate information on appliance lives and a larger sample. Employing the "accelerated-testing" method, a statistical technique developed to study the effects of operating conditions on the lives of durable equipment, we measured the effect of salinity on appliance lives. Then, total and marginal economic damages were estimated. Although marginal damages were expected to vary with salinity, it was surprising to find that marginal damages were highest at relatively low (200 mg/l) salinity concentrations. Economic damages were estimated to be less than those reported in previous studies. The difference in findings can be attributed primarily to technological improvements in appliances since the last major data collection efforts. The lower damage estimates are also likely due to the employment of improved statistical techniques and to more complete data on appliance lives. The results suggest a need for reevaluating the basis for federal salinity control programs.

EXECUTIVE SUMMARY

Dissolved mineral constituents (often called salinity or dissolved solids) occur naturally in both surface and groundwater when water flows over rocks and through soils. Salinity can be further augmented by human activities. High salinity levels are often found in rivers in arid and semi-arid areas which drain from sedimentary geologic formations with a high content of soluble minerals. Increasing human diversion and evaporative consumption of water cause salts to be concentrated in remaining streamflows, thus increasing salinity. Additional salts may be added by unused diversions ("return flows") from crop irrigation, which often percolate through saline soils before returning to rivers. Such conditions are common in the Southwestern United States. The Colorado River, which originates in the Rocky Mountains and flows southwesterly to Mexico, is a source of mineralized water for the largest affected American populations. However, higher levels of salinity occur. In the Arkansas Valley of Eastern Colorado, several communities rely on highly mineralized water supplies. Las Animas, Colorado, for example, uses water of a mineral content over three times as high as that in water supplied to Southern California cities from the Colorado River.

Salinity in residential water supplies has been identified as a source of reduced effectiveness and lowered service lives of household appliances in many areas of the United States. Damages can come from increased corrosion of metals which come in contact with water, scaling of contacted surfaces, higher costs for cleaning compounds, and diminished effectiveness in the use of water for productive activities. Households may also attempt to overcome the effects of salinity through increased expenditures for bottled water, for water softening, or for home water treatment to remove salts.

Total dissolved solids (TDS) in milligrams per liter (mg/l) is the most frequently employed measure of salinity. Previous studies have reported that economic damages can be detected at concentrations of 400-500 mg/l and above. However, TDS is a "macro" measure; the potential for causing damage depends in a complicated way on the concentrations of individual constituents. Sulfate and chloride are corrosion-accelerating substances that loosely speaking, for example, weaken and destroy metal pipes and parts. Hardness from calcium and magnesium can produce damages from scaling and from decreased cleaning effectiveness. On the other hand, a thin, uniform scale related to hardness can protect metal surfaces against corrosion.

Responses to the presence of minerals in residential water supplies can be either public or private actions or a combination of both. Individual householders may choose to endure the inconvenience and expense or take steps or incur expenditures to reduce impacts. Private responses can include selection of corrosion-resistant appliances, installation of water softeners, purchase of good quality water for drinking and cooking, or even investing in desalination units. Public or collective programs for abating salinity usually take the form of projects designed to reduce salt loading from either natural or human-made sources. One example is diversion of discharges from natural salt springs to evaporation ponds, while another is improvement of irrigation efficiency on farms to reduce saline wastewater return flows. Public salinity abatement may have an advantage of economies of scale not available to individual householders. Public programs are economically feasible in the cost-benefit sense if they are less costly than the sum of avoided private damages and private abatement costs.

Information on how salinity affects the service life of household appliances can be useful both to individual households and to those responsible for public policy regarding water quality. Households forced to use high salinity water supplies can benefit from improved knowledge in their decisions on whether to treat the water, to choose other actions (i.e., plastic components, more frequent maintenance, etc.), or to seek alternative supplies. Better information can help public water quality agencies assess the economic merits of alternative water quality management policies [Adams and Crocker, 1991; Pearce and Turner, 1990].

PREVIOUS RESEARCH

A surprisingly limited empirical literature attempts to quantify the economic damages from mineralized water supplies to residential water users. None of the data collecting efforts conducted to date appeared in the peer-reviewed technical literature. Two studies funded by the U.S. Department of the Interior were completed by consulting firms over 20 years ago (see Tihansky [1974] for a summary). Each study surveyed communities in the Southwestern United States affected by salinity to determine service lives of household appliances and fixtures as related to TDS levels. One of these efforts relied on data provided by appliance repair or plumbing businesses, while the second interviewed households.

The most extensive study of salinity damages was performed in connection with a cooperative effort between the U.S. Bureau of Reclamation and members of a multi-university group in the Colorado River basin in the mid-1970s [Andersen and Kleinman, 1978]. The chosen study design based damage estimates on opinions of appliance dealers and plumbers regarding the effect of salinity on appliance lives as did one of the earlier studies. Three locations in the Los Angeles area, as well as Las Vegas, Nevada and Phoenix and Tucson, Arizona were the sources of the observations. These data sources provided only a limited range of TDS, from about 450 to 750 mg/l. The per household damages per mg/l summarized in the report were much larger than any previously reported. These results were adapted to estimate economic benefits (damages avoided) and served as the justification for a federally funded abatement plan, embodied in the Colorado River Salinity Control Program.

Questions can be raised concerning the basic approach to both data collection and analysis in the Colorado River regional study. The use of judgments by plumbers and appliance repairers, rather than actual experiences by residents, has been challenged by some. The ages of in-service appliances were not taken into account. Estimates of adverse impacts were treated as linear with respect to salinity concentration (implying a constant marginal damage throughout the range of analysis), although the basic statistical analysis suggested a nonlinear relation above a threshold salinity concentration.

The most recent general data collecting effort to study residential demands from salinity is found in an unpublished doctoral dissertation [Coe, 1982]. Nine hundred households in four Southern California communities responded to a questionnaire. Maximum salinity in the sample cities was 700 mg/l. The author attempted to give special attention to constituent ions, but both questionnaire design and statistical analysis procedures could have been improved.

Lohman, et al. [1988] updated and extended previous studies for federal planning purposes in the Colorado River basin, but obtained no new primary user data. Damages estimated in this report were much higher than in any earlier study, even allowing for inflation. Bruvold and Daniels [1990] addressed the sensory quality (flavor, odor, appearance) of drinking water.

Several additional strands of relevant literature exist, in applied statistics, in survey research, and in the consumer science field, little of which has yet been drawn upon for studies of residential damages from salinity. Salinity damage studies have focused on age of failure of previously owned appliances, but have ignored the age of in-service appliances. At least two techniques allow the ages of in-service appliances to be taken into account in estimating the effects of salinity in appliance lives: the nonparametric product-limit method [Kaplan and Meier, 1958] and the parametric maximum-likelihood approach [Nelson, 1982]. Survey design, including factors which encourage accurate responses and estimates such as questionnaire construction and sampling procedure, has also improved in recent years [Dillman, 1978; Fowler, 1991].

OBJECTIVE AND OVERVIEW OF APPROACH

The purpose of this study was to develop improved techniques for measuring the damages to households from salinity in residential water supplies and to test these techniques on a significant case study region. We chose the Arkansas River basin in Central and Southeastern Colorado as the study area, because the range of salinity observed in household supplies is much wider than that addressed in previous studies. The Arkansas basin provides a natural experiment on the effects of salinity on residential water users, because it includes headwater communities enjoying low mineral concentrations (below 200 mg/l) and plains-area towns which experience salinity ranging up to 3500 mg/l.

We adapted and extended techniques previously developed in applied statistics to study the effects of water quality on the durability of household appliances. Improvements in sample design, questionnaire wording, and statistical analysis were drawn upon to more accurately measure effects of water quality on durability of household appliances. Observations across a wider range of salinity provided a better understanding of the functional form of the damages (i.e., whether damages are linear or nonlinear with respect to salinity). Our updated estimates reflect technological improvements in appliance durability and in household piping materials since data were last collected. We adapted and extended the accelerated-testing method to model the effect of salinity on the lifetimes of appliances.

DATA COLLECTION PROCEDURES

We selected mail surveys as the mechanism for data collection because this method provides the most satisfactory balance of cost and accuracy for the circumstances. Due to the large area to cover the necessary sample size and the number of questions we wished to pose, the personal interview approach would not have been feasible within the limited data collection budget. A mail survey allows respondents to think about questions and consult records if they choose and does not force respondents to reply instantly.

We developed three separate questionnaires to survey each of the following groups: households (consumers), appliance repairers, and plumbers. A fourth brief postcard questionnaire was developed to survey nonrespondent households. (Copies of each questionnaire are included in Appendix 2.)

Household questionnaire

The questionnaire mailed to households was titled "Water in Your Community: Quality and Costs." It was formatted as a booklet with a graphic, the title, and a message of encouragement to respond and appreciation for response on the cover. The questionnaire was divided into nine titled sections: (1) Water; (2) Around Home; (3) Your Water-Using Appliances; (4) Household Fixtures and Plumbing; (5) Laundry; (6) Your Car/Truck; (7) Bottled Water; (8) Value of Improved Water; and (9) You, Your Family, and Your Home. The survey sought information relevant to the quality of the household's water supply, the direct and indirect costs of that water and its use, and demographic data on the respondent and household. The statistical models estimated for this report are based on the responses from the household questionnaire.

Sampling procedures

In late July 1991, we sent questionnaires to a random sample of 2,226 households in ten communities along the Arkansas River in Colorado. Names for the sample list were obtained from telephone directories. At the same time, the questionnaires for appliance repair firms and plumbing firms were distributed in these same communities. For repair data, questionnaires were sent to 65 appliance repair firms and to 73 plumbing firms. At three-week intervals, those who had not yet responded were mailed a second questionnaire. Remaining nonrespondents were, after a similar interval, sent a third questionnaire. Finally, a sample of household nonrespondents were mailed a postcard nonresponse questionnaire to help determine if nonrespondents were similar to or different from respondents.

Response rates

Of the 2,226 household questionnaires, 872 questionnaires were returned and usable. The response rate was 44 percent when ineligible and undeliverable questionnaires were excluded. Of 65 questionnaires sent to appliance repair firms, 21 were usable for a response rate of 32 percent. Plumbing questionnaires were mailed to 73 firms; the response rate was 26 percent. The postcard questionnaire was sent to 515 households, half of those who had not responded to the questionnaire "Water in Your Community: Quality and Cost" after 11 weeks.

ANALYSIS OF THE EFFECT OF SALINITY ON APPLIANCE LIFE

The remainder of this report deals primarily with one important component of salinity damage to households: damage which results from early failure of water-using household appliances. We discuss the methods used in earlier studies to estimate appliance replacement costs, suggest techniques by which the estimates may be improved, and apply the suggested techniques to data obtained from the survey.

The survey of households asked, among other things, for both the ages of current appliances and the ages at replacement of previous ones. We propose an improved method of using data from a survey of households to estimate the effect of salinity on appliance life. The suggested method, which is based on a generalization of the established methods of "accelerated testing", allows the use of data on appliances still in service. We present accelerated-testing models of the effect of salinity on water-using appliances based on our survey of households.

The method of accelerated testing

At this stage, our general problem is to model the effect of an environmental variable on the failure behavior of some population of items. Here we consider the effect of salinity on household appliance life, for example, on water heaters. At a particular level of salinity, there is some probability distribution of water heater lifetimes. If data on actual life of water heaters at a particular salinity level are available, it is possible to fit, by the method of maximum likelihood, the life data to some simple parametric distribution function such as a Weibull, log-normal, or exponential distribution function. The distribution of lifetimes, by presumption, differs for different values of salinity. It would be possible to fit a parametric approximation at every level of salinity for which lifetime measurements are available. Conceivably, even the parametric form chosen for fitting would be different at different levels of salinity. However, such an approach would make it difficult to generalize about the effect of salinity on lifetime, particularly at salinity levels in between the levels for which life data are available.

A more useful approach, the accelerated-testing or life regression method, relies on a few simplifying assumptions. First, it assumes that the same parametric form is adequate at any salinity level within the range of the data. For example, a Weibull distribution might describe the failure behavior of water heaters at low salinity and at high salinity but with different values for the parameters of the distribution.

Next, the accelerated-testing approach assumes that the lifetime distributions at different salinity levels are related in a simple way: there is some scale factor that converts actual failure times to the amounts of time the units would have lasted if salinity had been zero. For example, if salinity is actually zero, then no scaling is required and the scale factor is unity. At some high level of salinity, the scale factor would be larger than unity: if a water heater lasting for ten years at 4000 mg/l salinity would have lasted 25 years at zero salinity, then the scale factor is 2.5. The scale factor as a function of salinity (the acceleration function) converts all of the life data, at all salinity levels, to the same nominal salinity level, that is, zero. The data can then be considered to have been generated by a single parametric distribution function; the parameters of which could be estimated by the method of maximum likelihood.

Yet, there remains a thread hanging. The form of the acceleration function and the values it determines for the scale factor are not known in advance. A particular functional form for the acceleration function must be chosen before proceeding. The standard accelerated-testing method uses either the linear or exponential form. Initial guesses for the values of the parameters of the acceleration function and the distribution function result in a particular value of the likelihood function. A different parameter vector generates a different value for the likelihood function. Various iterative numerical methods are available for finding the point in parameter space that maximizes the likelihood function and thereby indicates a good fit between the model and the data. All of the methods start with some initial guess of the parameter vector and attempt, step by step, to approach the point where the likelihood function is at a maximum. By employing a systematic search method, the accelerated-testing method simultaneously determines the best values for the parameters of the acceleration function and the parameters of the distribution function that holds at zero salinity.

Figure ES1 illustrates the application of a generalized accelerated-testing method to the case of water heaters employing the data collected from the Arkansas Valley sample described earlier. The Figure shows three types of analysis of water heater data. Simple arithmetic means of service lives as related to salinity ignore the information available from appliances which have not failed ("censored data"). The product-limit method (also called the Kaplan-Meier method) provides an estimate of the reliability function when not all units have failed. The product-limit estimates in Figure ES1 are for specific communities and are shown with error bars indicating the standard error of the mean life estimates. The smooth curve showing the accelerated-testing estimates utilizes all of the data together to produce a single function which applies at any salinity level. Both the product-limit method and the accelerated-testing method, by using data on the ages of appliances still in service, yield estimates implying longer appliance life than does the arithmetic mean.

Because ignoring censored observations results in underestimating the mean life of water heaters throughout the salinity range, we also expect plumbers and appliance

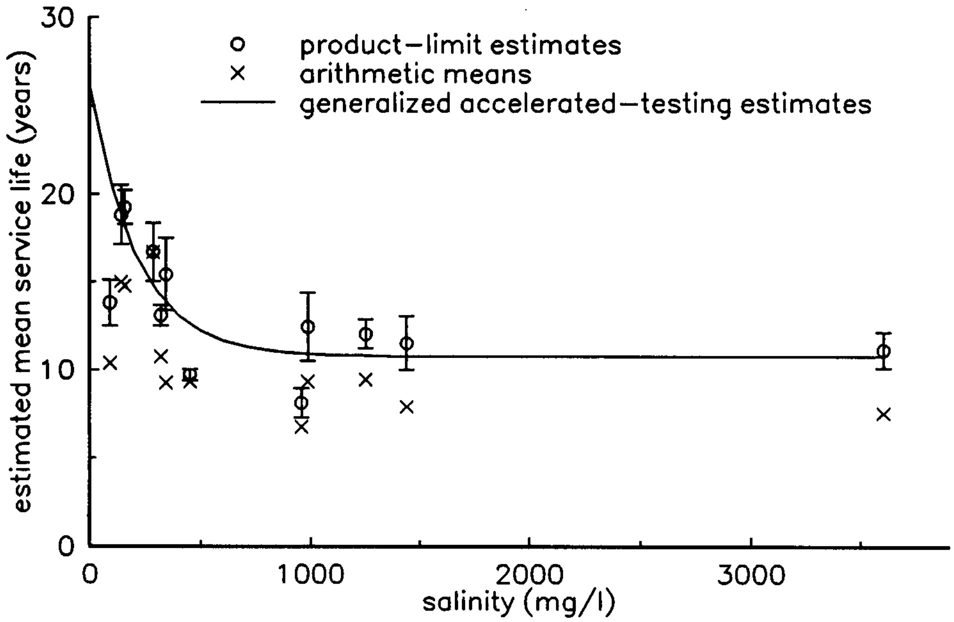

Figure ES1. The generalized accelerated-testing method applied to water heater data.

repair firms to underestimate the mean life of appliances. This is in fact what the data show; while the repairers' responses do demonstrate a declining life as salinity increases, the estimates of appliance life are systematically lower than those derived from the accelerated-testing procedure. This result, combined with the small number of respondents in the repairers' sample, leads us to discount the results of the repairers' sample and to suggest that future efforts concentrate on studying households.

Results of estimating life models of water-using appliances

We used the accelerated-testing method to fit the failure data from the household survey. Salinity was found to show a statistically significant effect on the lives of five appliances: water heaters, clothes washers, water softeners, garbage disposals, and evaporative coolers. No significant effect was found for dishwashers and humidifiers.

ESTIMATING THE AGGREGATE ECONOMIC DAMAGES AS A FUNCTION OF SALINITY

The final step in the empirical analysis is to determine the monetary value of damages to households from salinity. We draw on estimated local costs to replace individual household appliances combined with the previously derived results of the appliance life distributions. For example, the estimated mean life of water heaters at zero salinity (the mean of the life distribution at zero salinity) divided by the acceleration function gives the mean lifetime of water heaters as a function of salinity. Then, given the estimated cost of replacing water heaters, the mean lifetime as a function of salinity may be converted into expected annualized replacement cost as a function of salinity by simple division. The details of the relationship between appliance service life and annual cost are developed in the body of the report using different assumptions about the age distribution of appliances in a community. In the simplest and usually most realistic case, there is a steady-state distribution of appliance lifetimes and the annualized expected cost of replacement per household is given approximately by the price of the appliance divided by its expected service life. Multiply the expected annual replacement cost for a household by the fraction of households in a community having the appliance in question at all salinity levels to get the average annual per household expected replacement cost for the community as a function of salinity. Add similar cost functions for all appliances to get an aggregate replacement cost function for the community. The benefit to the community of an incremental reduction in salinity is then the difference in replacement cost between the two salinity levels.

CONCLUSIONS

In general, with the wide range of salinity in the Arkansas Valley and the availability of improved data collecting and analysis techniques, we were able to develop improved understanding of the effects of salinity on residential water users.

We begin with two conclusions of a methodological nature. First, the accelerated-testing approach is superior to the available alternatives for estimating the effect of salinity on appliance life. If the accelerated-testing assumption is accurate, the advantage of the accelerated-testing method over the product-limit method is that the former makes more efficient use of data; the product-limit method must ignore, at every salinity level, any in-service unit that exceeds the age of the oldest observed failure. Ignoring such data can lead the product-limit method to produce biased estimates of the mean life. The advantage of the accelerated-testing method and the product-limit method over the method used in previous salinity damage studies using household data (the arithmetic average of observed ages of failure) is the ability to account for in-service units and, therefore, to avoid the bias of overestimating the effect of salinity on appliance lives that can result from ignoring in-service units.

Second, household surveys appear to be superior as data sources to repairer surveys. Household surveys can provide information on lives of in-service appliances, more accurate information than repairers on age at failure, and a larger sample for statistical analysis.

From the perspective of policy aimed at improvement in water quality, two additional conclusions can be drawn regarding the magnitude and nature of the effects of salinity on households in the Arkansas Valley. First, damage from salinity appears to be less than that estimated in earlier studies. Taking water heaters, clothes washers, and garbage disposals together, the damage estimates reported here for those appliances are only about 40 percent as large as reported for the same appliances by earlier studies. There appears to be good reason to suspect that previous salinity damage estimates are too inaccurate (i.e., too high) to be used in evaluating current or future salinity abatement projects.

The reduced damage estimates arise from at least two sources. One source is methodological. The collection of more complete data and improved statistical techniques allow the use of less biased analytic procedures. The accelerated-testing procedure used with data on age of in-service appliances in addition to data on age at failure provides improved estimates of the effect of salinity of appliance lives.

Second, it is likely that innovations adopted in water-using appliances since earlier salinity damage studies were performed have reduced the potential benefit from salinity reduction. For one instance, extrapolated lifetime at zero salinity for three appliances modelled here is approximately twice that estimated by Tihansky (whose data comes from, among other places, a survey of households). Also, life models which are based on data from the 1960s and 1970s imply replacement costs due to salinity of nearly twice that estimated by the models developed in this study when using the same prices and saturation fractions. Moreover, technological innovations now in the pipeline (for example, water heaters with plastic and composite-material tanks) will almost certainly decrease further the adverse impacts of salinity on household appliances. In view of technological change, up-to-date estimates of salinity damage are necessary for accurately evaluating salinity damage for current or future projects.

A second empirical finding is that our estimated "marginal annual damage costs" as a function of salinity exhibits a rather surprising functional form. Marginal damage is important for economic evaluation of salinity control projects, because it measures the incremental gain from a salinity control effort which can be compared with incremental cost. Our own *a priori* conjectures were for a non-constant marginal damage function, but we expected that marginal damages would rise continually as salinity increased. Hence we selected our study area to focus on the higher range of salinity. However, the estimated marginal damages from our survey are at their maximum at around 200 mg/l, but fall rapidly until around 1000 mg/l, and change little at salinities above that point. (See Figure ES2.) The high marginal damage at low salinities is attributable mainly to two appliances: water heaters and water softeners. The marginal damages are not particularly sensitive to discount rate assumptions. A final note on the marginal damage function: at salinities in the range of policy interest in other basins—such as the Colorado—from around 700 to 1000 mg/l, our estimates of marginal damages are well below the peak values found, and as noted above, much below previous estimates.

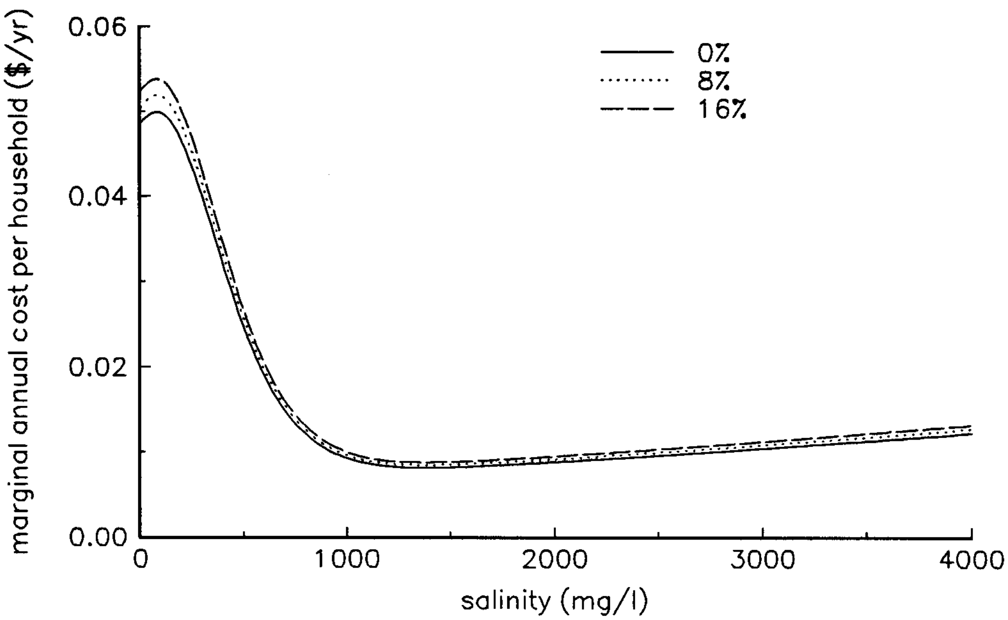

Figure ES2. Effect of the discount rate on marginal annual appliance replacement cost under the steady-state age distribution.

Further research needs

Several additional steps would have been desirable if sufficient resources had been available. We did not take into account the variations in concentrations of individual ions. The possible effects of softening on appliance life might be examined. Repair costs of appliances (in addition to replacement costs) perhaps might be significant. A sensitivity analysis of the effects of appliance prices on the estimated damages should be considered. Consideration of sensory characteristics (as initiated in Bruvold and Daniels [1990]) would be of value.

A useful next step would be to replicate the study in some other basin, such as the Colorado or in locations with differing ionic mixes. Such a study should begin with a detailed examination of the conceptual questions surrounding the definition of salinity damages in cases when consumers have an inexpensive option to lengthen appliance lives (as with pure water for car radiators or sacrificial rods in water heaters). A replication should help determine if marginal damages are indeed most important at low levels of salinity and whether present public salinity control policies are a productive expenditure of scarce public funds.

CHAPTER 1

INTRODUCTION

WHAT IS SALINITY AND WHY IS IT A PROBLEM?

Freshwater rivers and streams and flowing groundwater pick up soluble minerals, that is, salts, on their normal courses. Runoff and seepage from agricultural and urban irrigation further load river and groundwater systems with salts. Waters used for irrigation in arid and semi-arid regions may reach high levels of salinity due to evapotranspiration and the resulting concentration of salts in the remaining water.

High levels of salinity can adversely affect water users. Households suffer damages attributable to the salinity of their tap water. Household damages may be reflected in expenditures for bottled drinking water or home water treatment; damage to water-using fixtures, appliances, and pipes; increased expenditures for soaps and detergents; and additional work cleaning mineral deposits from fixtures. The salinity of irrigation water may reduce crop yields or induce farmers to grow salt tolerant crops which might otherwise be less profitable. In extreme cases, farmers might abandon their land due to the buildup of salts in the soil and groundwater.

WHAT CAN BE DONE ABOUT SALINITY?

One extreme case of saline groundwater led indirectly to the widespread recognition of salinity as a potential problem and a law authorizing agencies of the federal government to control the salinity of the Colorado River [Johnson, 1981; Miller and others, 1986, pp. 24-25; Reisner, 1986, pp. 480-483]. In the 1930s and 1940s, farming declined near the towns of Wellton and Mohawk in Southwestern Arizona due to a buildup of salts in the groundwater. In the mid-1950s, a federal water project had brought in irrigation water from the Colorado River to replace the groundwater. Farming again became difficult when the imported water caused the water table to rise and waterlogging in the crop root zone. Another federal project was instituted to drain, pump, and dispose of the saline groundwater into the Colorado River just north of the border with Mexico. At about the same time, the completion of Glen Canyon Dam and the filling of Lake Powell behind it reduced the flow of the Colorado below the dam and thereby reduced the dilution of the drainage from the Wellton-Mohawk area. The Colorado River entering Mexico reached a salinity of 1500 mg/l in 1962, twice its usual level. Mexican farmers suffered crop damage and the Mexican government claimed that a 1944 treaty with the United States had been violated. The United States responded by negotiating a new treaty with Mexico and by passing the Colorado River Basin Salinity Control Act (Public Law 93-320) in 1974. The law authorizes the U.S. Bureau of Reclamation and other agencies of the federal government to spend public money to control the salinity of the Colorado River. In the latest stage of the federal response to the water quality crisis with Mexico, the Bureau of Reclamation is building a reverse-osmosis desalination plant to treat the pumped saline groundwater from the Wellton-Mohawk area before it enters the Colorado river [U.S. Department of the Interior, 1983, 1991].

Other means of addressing the salinity problem under the Colorado River salinity control program include irrigation efficiency improvement programs and reductions in irrigated acreage; pumping and disposing of (by deep well injection or solar evaporation) saline ground water; measures for reducing seepage from stock watering ponds, irrigation canals, and laterals by lining and installing pipes; channelling wastewater around saline deposits; and developing industrial uses for saline water.

Public investment has also been considered for the Arkansas River in Colorado where, with little fanfare, salinity levels routinely exceed the levels that provoked the crisis with Mexico over the Colorado River. The Fryingpan-Arkansas project which consists of a transmountain diversion and several reservoirs (including Pueblo Reservoir) was originally designed to include a pipeline to transfer water of moderate salinity (300-400 mg/l) from Pueblo Reservoir for municipal use in communities downstream where the salinity level in the river sometimes reaches 4000 mg/l [Black & Veatch, 1972; Cress, 1989]. The Bureau of Reclamation is now considering a research and development program for desalination plants and might use one of the cities in the Arkansas Valley as a testing ground. The State of Colorado has designated an area near Canon City in the Arkansas Valley as one of nine critical agricultural areas in the state due to the severity of the salt-loading problem there. The designation makes landowners eligible for cost-sharing assistance for reduction of salt loading under the Rural Clean Water Program [Colorado Department of Local Affairs, 1980, p. 46].

Local water utilities and householders can also decide to reduce salinity. Home-scale water softeners, reverse-osmosis water treatment devices, and distillers are available. Householders could conceivably take the potential for salinity damage into account when deciding where to live. Local water utilities might consider diversion projects or desalination of surface water or groundwater. For example, the city of Las Animas, Colorado, on the Arkansas River, has been considering installing a reverse-osmosis desalination plant.

WHAT SHOULD BE DONE ABOUT SALINITY PROBLEMS?

Little notice has been taken of the salinity of the Arkansas River as compared to the Colorado despite much higher salinity levels in the Arkansas. Why? The fact that the salinity of the Arkansas River falls as the river enters the more humid areas in the east is no doubt important; Kansas is not a foreign country. Also, the population affected by high salinity levels is small compared to the population served by water from the Colorado River, notably the parts of Southern California served by the Metropolitan Water District. The major towns in the Colorado portion of the lower valley (Rocky Ford, La Junta, Las Animas, and Lamar) have a combined population of less than 25,000.

But there seems to be something more. On an agricultural tour of the Arkansas Valley led by Frank Milenski, a locally prominent farmer and water activist from near Rocky Ford, Colorado, no mention was made of salinity, until the topic was broached by a researcher. Milenski did not seem to be greatly concerned about it. Indeed, in his book about the history of irrigation on the Arkansas River in Colorado, salinity is hardly discussed.

> It seems to me that the good Lord had some pretty good ideas when this river was formed, but everyone wants to change it. The EPA is always talking about salt load and erosion and everything. . . You start up in the mountains and your water is real good quality; when you get down to about Las Animas what do you get? Over two or three thousand parts per million of hardness in the water. Nature created that—it's always been that way. You ain't gonna change it [Milenski 1990, p. 100].

Concerning transfers of water out of the basin, he says

> Water quality tests show that the salinity level (concentration of total dissolved solids) is now about 150 parts per million (ppm) above the Pueblo Reservoir, and 2000 to 4000 ppm down river at Lamar. As smaller and smaller amounts of clear mountain water flow out of the Pueblo Reservoir, there will be less flushing activity down river and the water quality levels may get much worse (p. 148).

On the proposed pipeline, he says

> Originally, they also discussed putting in an Arkansas Valley pipeline at a cost of seventeen million dollars, but the last figures I have heard on it were already up to seventy-nine million dollars . . . St. Charles Mesa and La Junta decided they didn't want to go on the pipeline. It seemed too much cost for too little water. And I don't think you will ever see the Valley pipeline built (p. 106).

One reason farmers may not be terribly concerned about salinity in the Arkansas Valley of Colorado might be that after decades of high salinity levels, farming practices and even seed varieties have adjusted to the salinity levels. Salt resistant strains of pinto beans, normally considered to be a salt sensitive crop, have been developed in the Arkansas Valley of Colorado after decades of selecting local seed [Miles 1977, p. 54]. On the other hand, Mexican farmers on the Colorado River were hit with a sudden more than doubling in the salinity of their irrigation water.

One possible partial answer to the question of what should be done about salinity is that public investment in salinity control should only be undertaken if the benefits appear to exceed the costs. However, the Colorado River Basin Salinity Control Act of 1974 is not set up on a cost-benefit basis: the economic benefits of salinity control are not explicitly required to exceed the costs. Nevertheless, the responsible agencies have shown a continued interest in measuring the benefits of salinity reduction. When considering salinity reduction projects, managers of water utilities also want to know the expected benefits. If salinity reduction is to be paid for by rate payers, utility managers will consider that a project showing a positive net benefit will be more likely to gain approval from voters and their representatives. If salinity reduction is to be aided by state or federal subsidies, the importance of a net benefit is smaller from a local point of view. In fact, a perverse cost-benefit accounting could arise on the local level: costs to the outside funding agency, such as labor costs and local purchases of materials, might be counted as benefits to the local community. And once the prospect of the federal government paying the full cost of salinity reduction arises, some local residents (seeking opportunities for employment or expansion of existing businesses) would have an incentive for exaggerated claims of the benefit of reduced salinity.

Water utility managers will in some cases want to assess the cost of increased salinity. For example, the Metropolitan Water District serving southern California augments its water supply with water from the Colorado River which is higher in salinity than other sources of its water.

For estimating the benefit of salinity reduction, a few salinity damage studies, many of them funded by agencies interested in promoting salinity reduction, are available. The studies indicate that the early failure of water-using appliances is an important part of the cost of salinity. For example, according to computations by Lohman and others [1988, p. 69] damage to water heaters, garbage disposals, clothes washing machines, and dishwashers account for 16 percent of total household salinity damages in the Colorado River basin in 1986.[1] Again, according to computations by Lohman and others the costs of home water softening accounts for about 41 percent of household damages (excluding automobile radiator damage). A large part of the cost of home water softening is the capital cost, which is included in the cost computations in the present work.

The theoretical foundation upon which previous studies built estimates of the cost of appliance replacement may be improved in three ways: (1) by accounting for the random timing of appliance replacement expenditures, (2) by considering the effect of changes in salinity on the effective age distribution of appliances, and (3) by including information on appliances still in service. We will suggest improved methods of data reduction based on an expanded theoretical foundation. Because the suggested methods require the collection of data on appliances still in service, surveys of households are preferred to surveys of plumbers and appliance repair firms. We will also suggest that, for additional reasons unrelated to the methods of data reduction, household surveys might be better for estimating appliance life than surveys of plumbers and appliance repair firms.

With one exception, previous studies rely on data collected between the mid-1960s and mid-1970s; new technologies in water-using appliances have appeared since then. Innovations such as the introduction of plastic pipes and water heaters

[1] We have excluded the contribution from automobile cooling systems.

with plastic or composite-material tanks underscore the importance of up-to-date information on salinity damage to appliances.

OBJECTIVES, SCOPE AND PLAN OF REPORT

The purpose of this study was to develop improved techniques for measuring the damages to households from salinity in residential water supplies and to test these techniques on a significant case study region. We chose the Arkansas River basin in Colorado as the study area, because the range of salinity observed in household supplies is much wider than addressed in previous studies. The Arkansas basin provides a natural experiment on the effects of salinity on residential water users, because it includes headwater communities enjoying low mineral concentrations (200 mg/l) and plains-area towns which experience salinity ranging up to 3500 mg/l.

We applied techniques previously developed in applied statistics to study the effects of water quality on the durability of household appliances. Improvements in sample design, questionnaire wording, and statistical analysis were drawn upon to more accurately measure effects of water quality on durability of household appliances. Observations across a wider range of salinity should provide a better understanding of the functional form of the damages (i.e., whether damages are linear or nonlinear with respect to salinity). We expected updated estimates to reflect technological improvements in appliance durability and in household piping materials since data were last collected. We adapted and extended the accelerated-testing method to model the effect of salinity on the lifetimes of appliances.

We surveyed households, plumbers, and appliance repair firms in the Arkansas Valley of Colorado by mail in the summer of 1991. Our surveys gathered information on a wide range of possible contributions to salinity damage.

We examine in depth here primarily one important component of salinity damage: the early failure of water-using household appliances. We examine the methods used in previous studies to estimate appliance replacement cost, suggest techniques by which the estimates may be improved, and apply the suggested techniques to data obtained from the surveys.

CHAPTER 2

REVIEW AND ASSESSMENT OF PREVIOUS SALINITY DAMAGE WORK

Olson [1939] speculated on the economic costs to households of salinity, specifically hardness. Olson's paper constitutes a catalog of possible damages to households and businesses from hardness. However, his objectivity may be questioned if the following statements are considered. "Some systematic course needs to be followed to stimulate the public's desire for soft water" (p. 632). One advantage of soft water cited is "increased revenue to the plant" (p. 635).

Olson's primary conclusion is that "the greatest monetary saving is in that of soap and cleaning compounds used in commercial enterprises as well as in the home" (p. 634). Soap reacts with calcium and magnesium to form an insoluble precipitate or scum. The formation of the precipitate consumes some of the soap, so more soap must be used in hard water. Furthermore, the precipitate itself dirties the object and may not be rinsed away. In clothing washed with soap, the precipitate can, according to the article under review, remain embedded in the clothing and increase the rate of wear and tear. This might result in reductions in clothing lifetimes of from 17 to 33 percent (p. 621).

> Synthetic detergents do not encounter such severe problems with hard water. The decline in detergency with increasing water hardness is most dramatic with soap. Sensitivity to water hardness largely disappears in phosphate- and zeolite 4A-containing formulations of the commonly used detergents because of sequestration binding or ion exchange of the hardening agents [Jakobi and Lohr, 1987].

Synthetic detergents began to appear in the late 1920s and early 1930s but apparently were not in general use for clothes washing, dishwashing, hair shampooing, or any other household or commercial uses when the article was written. Synthetic detergents have almost completely replaced soap for washing dishes and clothing. Soap is now used for washing hair only in a pinch; nonsoap liquids and bars are available for washing the skin. What Olson considered to be the major costs in 1939 may have all but vanished.

Other problems with hard water are still with us. Olson lists wear and tear on cooking utensils, effect on the cooking of vegetables, cost of home softening, elimination of duplicate plumbing (where cisterns are in use for storing rain water), repairs to plumbing and water heaters, additional fuel cost in gas water heaters, and damage to car radiators and exterior finishes. Olson observes one means of avoiding salinity damage to radiators:

> In the hard water belt of Florida one of the nationally known oil companies has small-sized domestic softeners in each station for furnishing soft water for radiators. This is also the case in other localities where conditions demand removal of impurities (p. 631).

The engineering firm Black & Veatch performed, for the U.S. Office of Saline Water, one of the first reasonably comprehensive attempts to measure the economic effects of tap water salinity [Black & Veatch, 1967]. The investigators point out that they do not include effects caused by constituents that are "readily and economically removed or neutralized in conventional water treatment processes" (p. 1). Therefore, they exclude the effects of hardness and of trace minerals including the costs of home water softening and damage from staining. The investigators visited 38 municipalities in the West and Midwest to collect data for the study. Three of the communities they visited are in the lower Arkansas valley of Colorado: La Junta, Las Animas, and Rocky Ford.

The investigators warn that "the information obtained, while of limited reliability requiring significant interpretation, did result in a substantial amount of data of an indicative nature." Furthermore, they write, "it is emphasized that due to the fact that there is a lack of specific data, values developed are based primarily on the experience and judgement of the investigators" (p. 2). The Black & Veatch investigators base many of the cost estimates on what they present as an arbitrary factor. For example, take the economic effect that they claim to be the greatest single contributor to the economic damage of salinity: reduced lifetimes of clothing. The following is the only justification they give for the difference in the added cost of clothing replacement: "A 5 percent reduction in the estimated life of washable fabric is allowed in Table 5." To be fair, we should acknowledge that the investigators warn that, "because of the somewhat speculative basis for estimating the reduction in fabric life due to minerals, care should be taken that unwarranted emphasis is not placed on this effect" (p. 41). However, the conclusions of the study rest on other calculations of this sort. For example, when calculating the increased maintenance costs of washing machines, garbage disposers, dishwashers, water heaters, toilet flushing mechanisms, faucets, and piping, the investigators guess a fixed number of repairs for each item during its lifetime. When their interview data suggest a difference in lifetime, the implied frequency of repair changes accordingly. They offer no justification for the guesses or for the assumption of a fixed number of repairs per lifetime. The following quote is an example of the methods used to construct the cost estimates.

> The specific effect of increased minerals has not been measured but for this report an increase in soap and detergent cost of 10 percent, or $4 per year is allowed as the excess cost of cleansing agents due to highly mineralized water supply exclusive of the effect of hardness (p. 36).

The report does contain valuable background information on the kinds of problems caused by salinity in a wide array of municipalities with widely varying tap water supplies. Particularly valuable as background are the summaries by municipality contained in its Appendix C [Black & Veatch, 1967].

A few years after the Black & Veatch report, the Office of Saline Water hired another engineering firm, Metcalf & Eddy, to perform a similar study [Metcalf & Eddy, 1972]. The study makes use of a mail survey of households in ten selected municipalities in California, Texas, Florida, and Colorado. Salinity in the municipalities ranges from 32 to 3300 mg/l. The proportional mixture of ions also varies considerably, which opens to the researchers the possibility of statistically observing the separate effects of different ions. The researchers single out hardness and total dissolved solids (TDS), that is salinity, as a pair of water quality descriptors that adequately describe a water from the point of view of salinity damage.

The mail survey consisted of one page asking for the following information:

(1) type of dwelling
(2) age of dwelling
(3) number of residents in dwelling
(4) whether washing machine is owned
(5) whether dishwasher is owned
(6) how much is spent per week on detergent, soap, fabric softener, and water conditioner
(7) whether home water softener is in use
(8) cost of water softener operation
(9) whether bottled water is bought
(10) how much is spent per month on bottled water
(11) whether hot water heater has been replaced, and how old it was at time of replacement
(12) whether there are any objectionable characteristics of the tap water, and an explanation of these.

Note that the investigators can discover nothing about the lifetimes of washing machines, dishwashers, and water softeners from the survey. They rely on "water experts, equipment manufacturers, and research oriented groups" to infer data relevant to aspects of home water damage not covered in the survey (p. 4). After factoring in the expert information, the investigators conclude that

> no significant correlations between cost and water quality are evident for damage to clothing, dishes, glassware, . . . lawns, plants, . . . plumbing repair and replacement, . . . [and] bottled beverages (excluding bottled water)" (p. 8).

In computing the equivalent monthly replacement costs of water heaters and water softeners, the Metcalf & Eddy investigators ignore the time value of money. This is consistent with assuming a uniform appliance age distribution that immediately changes to a new steady state upon a change in salinity [Booker, 1990, pp. 102-106]. There will be more discussion of this point in Chapter 5.

The study seems to be an improvement upon the Black & Veatch study, as the Metcalf & Eddy study does glean some information from households and relies less upon nebulous experts. Nevertheless, the failure to indicate where exactly the expert knowledge comes from gives a good reason for lack of confidence in the conclusions of the study. Note that the effect on clothing, which Black & Veatch find to be highly important, Metcalf & Eddy find to be of no importance. In neither case do the investigators present evidence to back up their claims.

The study by Metcalf & Eddy does contain useful information about some general effects of water quality on households. Of particular relevance to the present study is the fact that Las Animas is one of the surveyed municipalities. In fact, the Metcalf & Eddy investigators mailed a survey form to every household in Las Animas. Las Animas turns out to be anomalous with respect to the other communities surveyed. The investigators obtain most of their respectable statistical fits by excluding Las Animas and Fort Morgan, Colorado. One reason they suggest for the anomaly is that 45 percent of the Las Animas sample have private soft-water wells or use laundromats for laundering (p. 48).

Tihansky [1974] uses data from the two studies just reviewed [Black & Veatch, 1967; Metcalf & Eddy, 1972] to estimate total household salinity damages by state of the United States. Tihansky uses a consistent and reasonable method to model life data as functions of salinity, and in so doing, improves upon previous studies. Nevertheless, his results are still subject to skepticism given doubts about the accuracy of the original data.

McGuckin, in his master's thesis [1977], using data on appliance failure time published in the report by Black & Veatch, attempts to improve upon Black & Veatch's and Tihansky's later statistical models of the same data. McGuckin fits functions of salinity, which are linear or transformably linear in the parameters, to the data: linear, power function, pure exponential, and second degree polynomial. (Tihansky uses transformably linear and exponential-plus-constant ($f(x) = c + ae^{bx}$) functions to fit the lifetime data.[2])

The choice of functional form implies certain behaviors which can not necessarily be definitively established by the data. Finding the best function to represent the data is not a matter purely of minimum least squared error or maximum likelihood. The function should exhibit reasonable properties in the range of the data and preferably beyond this range. In the absence of a rigorous model of the mechanism producing the data, one should rely heavily on visual evidence and reject functions that produce unreasonable deviations from prior expectations. Statistical measures of goodness of fit may be used to choose between functions that pass the test of reasonableness.

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[2] Although the exponential-plus-constant function is intrinsically nonlinear, Tihansky makes it transformably linear by choosing reasonable looking minimum and maximum lives, points through which the curve was required to pass. Therefore, his fits are not least squares fits to the general exponential-plus-constant form, except, perhaps, by accident. There may be a typographical error concerning Tihansky's reported water heater life model. Either he reports two distinct models, one in the text and in his Figure 1, and another in his Table 3, or there is a typographical error in his water heater model in Table 3. The discrepancy could be explained by 2.7 having been accidentally written as 2.4 in his water heater model in Table 3.

McGuckin does not reproduce the raw data in his thesis. He plots the fitted functions, unaccompanied by the data from which they are derived. The reader is liable to be left wondering whether the data actually exhibit the behavior implied by the functions displayed or the behavior is simply an artifact of the chosen functional form. Based on a visual comparison of the data as presented by Black & Veatch with the functions obtained by McGuckin, it appears that the supposed increasing lifetime of water heaters and galvanized iron pipe with increasing salinity reported by McGuckin is more reasonably seen as an artifact of the functional form, namely, the second degree polynomial.

The U.S. Department of the Interior and Water Resources Centers in Arizona, California, Colorado, and Utah funded a comprehensive study of the economic effects of salinity and salinity control in the Colorado River [Andersen and Kleinman, 1978]. In a section of the report produced by the study, d'Arge and Eubanks address the damages to municipal users from salinity [Andersen and Kleinman, 1978, Appendix 4 and pp. 19-24]. D'Arge and Eubanks intentionally sought waters with a proportional mixture of ions similar to that in the Colorado River. Therefore, consideration of the separate effects of specific ions was neither possible nor necessary, and the only water quality measure required was TDS. Three locales in the Los Angeles area were included for a comparison of costs versus salinity: Costa Mesa - Newport Beach (TDS = 728 mg/l), San Fernando Valley (TDS = 210 mg/l), and, for portions of the study, Long Beach (TDS = 759 and 457 mg/l, two locations). In the same document that reports the work of d'Arge and Eubanks, Andersen and Kleinman [1978, p. 21] report on a salinity damage study in two other groups of locations that used the questionnaires developed by d'Arge and Eubanks: Phoenix and portions of the Las Vegas metropolitan area (TDS = 735 mg/l) and Tucson and other portions of Las Vegas (TDS = 500 mg/l). D'Arge and Eubanks collected information on consumer costs from surveys of plumbing contractors and appliance repair firms. They did not survey households. They accounted for socioeconomic factors by dividing the three areas into sectors composed of combined census tracts with each sector having a population of 12,000 to 17,000 people. The socioeconomic variables were median home value, median contract rent, number of persons per household, percentage renter occupied units, percentage of housing units ten years old or older, and percentage of housing units 20 years old or older (p. 259).

D'Arge and Eubanks report that the southern California study yields costs of salinity "two to three times higher than those previously reported in the water resource literature" (p. 253). They find that salinity has a statistically significant effect on the lifetimes of water heaters, galvanized water and wastewater pipes, dishwashers, clothes washers, garbage disposers, and brass faucets. They find no significant effect for toilet flushing mechanisms and copper and plastic water and wastewater pipes. They estimate appliance replacement cost as the present value of a stream of periodic replacement expenditures. Booker [1990, pp. 102-106] shows that the discounted-expenditure-stream approach is consistent with the assumption that all appliances are new at the time of a change in salinity. (Further discussion of this point is in Chapter

5.) D'Arge and Eubanks report that socioeconomic factors are not significant predictors of appliance lifetimes with the exception of the negative effect of a greater number of persons per household on water heater lifetimes. The separate study in central Arizona and Las Vegas involves a much narrower band of salinity, 500 to 728 mg/l, and only two different values of salinity. As one would expect, the effects of salinity are less observable.

A doctoral dissertation by Coe [1982] describes his survey of households, plumbing contractors, appliance service centers, retailers of home water softeners, and bottled-water distributors in four Southern California municipalities. The scope of the surveys is far more extensive than the surveys conducted by Black & Veatch and Metcalf & Eddy. Even so, as Coe points out, his household survey lacks questions about the repair and replacement of dishwashers and garbage disposers (p. 145). Coe obtained information about repair and replacement of dishwashers and garbage disposers with his other surveys, but he does not use it in his statistical models (p. 105). Coe uses information from the survey of households, augmented by information from his other surveys, to build statistical models.

The waters of the municipalities chosen by Coe have high correlations between their ionic constituents. For example, for TDS and hardness, he reports a correlation coefficient of 0.93. He nevertheless chooses to attempt to separately estimate the effects of various constituents (p. 104). He does not address the possible problem with his estimates that might result from the multicollinearity, which is, of course, high variance in the parameter estimates and a consequent lack of statistical significance of the parameter estimates. He chooses to "recognize the multicollinearity, but do nothing else" (p. 104). Coe estimates several single and multiple regression equations, to be discussed below, but ends up favoring a simultaneous equation model.

The first equation in Coe's "explicit" simultaneous equation model has total cost (a sum of costs indicated from the consumer survey) as a linear function of the concentrations of hardness, TDS, chloride, and manganese, family size, and house value.[3] The second equation in his two-equation simultaneous model has willingness to pay (the answer to his WTP question[4]) as a function of hardness, concentrations of dissolved oxygen, sodium, and manganese, family size, house value, and total cost (from the first equation). The system estimated by Coe is recursive, because the first equation can be estimated in the absence of the other, while the second equation requires the estimated dependent variable from the first equation as a function of its independent variables. Coe offers no justification for this particular simultaneous

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[3] Coe also estimates an "implicit" model which does not contain any water quality variables directly, but includes certain "smoothed" costs (estimated from partial equations described below), such as of bottled water and of soap, as regressors. This model seems to be a needlessly complicated elaboration on a theme.

[4] "How much additional would you be willing to pay monthly for top quality water not requiring softening or purchase of bottled water?" [Coe, 1982, p. 163].

model. Why are sodium, manganese, and family size included in the second equation, when they are included implicitly in the total cost term? Why should anything influence willingness to pay besides total cost? Why is dissolved oxygen not included in the first equation when it is known that dissolved oxygen is "one of the most common and important corrosion agents" [American Water Works Association, 1990, p. 1044]. The only reason Coe offers for choosing a simultaneous model is that higher R^2 values are obtained (p. 120). High R^2 values say nothing about the usefulness of the model for estimating damage to households in situations not covered by the data used to generate the model.

Although some of the regressors are highly correlated and correspond to insignificant parameter estimates, the parameter estimates are not, for that reason, biased. As long as no meaning is attached to any of the parameter estimates, the model may still be useful. But the comparison of water qualities then requires knowledge of the various constituents. Yet, as the concentrations of ions in Coe's waters were highly correlated with each other, there is no reason to expect the model to apply to waters with very different proportional mixtures of ions. Therefore, more work is required by the user of the model with no additional payoff. In fact, the need for the user to supply several water quality measures might lead a user to believe the model to be more generally applicable than it is.

Coe also reports the results of several partial models that relate various cost items, such as detergent use, to water quality parameters. Based on the high correlation between water quality parameters, Coe groups them into two categories, the members of each category being highly correlated with each other: (1) TDS, hardness, chloride, sulfate, and sodium, and (2) iron and manganese (p. 104). After making this categorization, Coe could have chosen a representative from each category to include in the regressions. Instead, Coe allows more than one representative from each group. The result is a lack of significance of important parameters. Thus, Coe does not find the cost of soap and detergent to be significantly related to hardness or TDS (p. 106). Nor does he find the cost of bottled water to be significantly related to hardness, TDS, or iron. After noting the lack of significance of various parameters, Coe drops all variables having insignificant parameters (p. 114). From the model involving the cost of soap and detergent, he drops both TDS and hardness as well as house value, leaving only family size. As a result R^2 falls from 0.95 to 0.85, indicating that, perhaps, including either hardness or TDS but not both might have resulted in a significant parameter estimate for the effect of salinity on soap and detergent cost. Coe rationalizes the lack of significance of both parameters by explaining that modern detergents, the major component of soap and detergent costs, work just as well in hard as in soft water (p. 123). Perhaps they do. But Coe's faulty statistical method does not demonstrate the claim. Coe is lucky sometimes, when brute facts overwhelm his faulty method. For example, the home-softening model is left with a parameter representing hardness.

The most recent salinity damage study is one funded by the Bureau of Reclamation to "update, revise, clarify, and refine" the salinity damage estimates from the Andersen and Kleinman study mentioned above [Lohman and others, 1988]. The authors recognize the "deficiencies" (p. 1) of the salinity damage data available (the study by Andersen and Kleinman and other studies available at that time). But the level of funding of the study did not allow generation of primary data. Lohman and others estimate replacement cost as the price divided by the expected lifetime. The report contains a comprehensive bibliography of salinity damage studies and related literature.

Lohman and the other authors criticize the implicit definition of "damages" used in previous salinity damage studies. The implicit definition equates damage with any negative effect of salinity, detectable by its absence in pristine water, or water of salinity below any threshold that might exist for negative effect. The authors prefer to define damage as any negative effect above some arbitrary baseline, such as the "natural TDS level caused by natural point and diffuse sources at Hoover Dam" or the "EPA Secondary Drinking Water Standard" (p. 3). Lohman and the other authors engaged in "intense discussion" and considered 13 candidate values, in an attempt to choose the right baseline. They considered, for example, 186 mg/l (the average salinity of water supplied to the 100 largest cities in the United States); 334 mg/l (the natural salinity of the Colorado River at Hoover Dam based on the 1942-1961 geological record); 500 mg/l (the U.S. Environmental Protection Agency's voluntary secondary standard); and 825 mg/l (the maximum salinity projected for Parker Dam in 2010) (pp. 3, 13).

The authors state that the conventional approach, based on the presumed faulty definition of salinity damage, has been taken with "little justification" (pp. 2, 11). It is true that previous investigators have not specifically articulated a justification of the conventional approach. However, this is not to say that the approach is not justified. One way to justify the approach is to express the idea more precisely in terms of "damage from increased salinity" or "benefit from reduced salinity" instead of "damage from salinity." Provided that a reduction of salinity cannot be harmful, benefit of salinity reduction would accrue (beyond some arbitrary baseline) until zero salinity or a damage threshold were reached. The conventional approach is an economic approach because it recognizes that a foregone benefit is a cost, that is, a damage.

In practice, because differences in salinity are what matter, the conventional approach does not differ from the approach recommended by Lohman and the other authors as long as there is no proposal to reduce salinity below the arbitrary baseline, whatever it might be. If the method recommended by Lohman and others was applied to a reduction in salinity taking place entirely below the baseline, a benefit of zero would be estimated. If it were applied to a reduction in salinity from above the baseline to below it, only the portion above the baseline would count as a benefit. On a basin-wide scale, where low levels of salinity would probably not be achieved, their method might pose no problem. However, the economics of municipal and household treatment (for which salinity levels below the baseline might well be contemplated) could lead to the absurd result of no estimated benefit from a large reduction in salinity.

The authors claim that the effect of saline water on automotive cooling systems is an important cost of salinity. Their estimate of annual household salinity damage in

1986 due to the salinity of the Colorado River above 334 mg/l includes fully $117 million from car radiators out of total damages of $430 million, that is, 27 percent from car radiators alone. The authors appear to write from outside the well-developed theory of environmental policy [Baumol and Oates, 1975] and the approaches to measuring benefits of environmental improvement [Freeman, 1982; Peskin and Seskin, 1975] Therefore, they have not recognized that an upper limit to salinity damages to an automotive cooling system is the cost of buying a few quarts of distilled water per year: a negligible expense, especially for those already having home purification systems. The authors have not actually shown that people behave in such a way as to suffer salinity damage to their radiators that could have been avoided at less cost.[5] Rather, they base their damage estimates on a worse-case scenario in which everyone uses tap water in their cars, no matter what its salinity.

Damage to automobile radiators above the cost of bottled water that would be required to operate them properly should not be counted as salinity damage. The damage above that level is properly attributed to ignorance of the effects of salinity. Consider a case in which a salinity reduction project can be justified if radiator damages are included at the level estimated by Lohman and others, but not if radiator damage is valued at the cost of bottled water for all radiators. The project could be separated into two alternative projects: (1) the salinity reduction project and (2) a rebate to every affected household in the amount of the cost of supplying pure water for their radiators, with an accompanying note advising that the money be used for protecting car radiators with pure water. As, by assumption (ignoring administrative costs), project (2) is less expensive than the radiator damage estimated by Lohman and others, the opportunity cost of the radiator-damage avoidance in project (1) can be no greater than the cost of project (2). Therefore, the cost of project (2) could be counted as an upper limit on the benefit of project (1) corresponding to the reduction of damage to car radiators. The benefit may well be less than the upper limit, especially for changes in salinity that do not make it prudent to switch from bottled water to tap water.

A similar point, which applies to all salinity damage studies, can be made about corrosion of water heaters. Water heaters are designed to be protected from corrosion by means of a rod composed of a metal, such as magnesium, that is less noble (on the galvanic scale) than the other metallic water-contacting components of the heater. The rod becomes a sacrificial anode in a galvanic corrosion cell, corroding in preference to the other metal surfaces inside the heater or in nearby connected piping. Once the rod is mostly consumed by corrosion, protection is lost. The rod can be replaced to afford a longer period of protection. Presumably, replacing it when it is consumed, rather than allowing the heater to fail due to internal corrosion in the absence of a sacrificial anode, saves the consumer money. However, many if not most consumers are not aware of the option. On the other hand, awareness of the option might already be widespread in areas with high salinity tap water. Manufacturers also recommend

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[5] Recall Olson's evidence to the contrary: softened water at filling stations.

periodic flushing of water heaters. Failure to do so where salinity is high could lead to accumulation of loose scale and premature failure of the tank. Apparent damage to water heaters from salinity could, perhaps, be reduced if knowledge of the maintenance options were more widespread.

In some waters, in Las Animas, Colorado for example, the anodes color the water and cause it to taste bad [Black & Veatch, 1967, pp. c-12 to c-19 and p. 8]. According to Black & Veatch, in Las Animas the anodes are actually removed before the water heaters are put into service. The Black & Veatch investigators attribute the taste and color to the high concentration of sulfate in the water, which reacts with magnesium anodes to produce hydrogen sulfide gas.

Emerging technology in water heaters promises to greatly reduce salinity damage in the near future. Water heaters with plastic tanks have been developed. Sears, Roebuck and Company is now selling water heaters with metallic tanks lined with a composite material. Sears promises that, with the new seamless lining, the tank "should last longer without the anode rod" and this will "eliminate the rotten egg smell that can occur when certain water reacts with the anode rod" [Sears 1992/1993 Fall/Winter Annual catalog, p. 1100].

Booker argues that, if Lohman and others' estimates are accurate, residents of Los Angeles should be more concerned about salinity than is evident:[6]

> If salinity were recognized to be as damaging as these figures indicate, significant pressure to limit imports of Colorado River water would be expected, particularly in years of high Colorado River salinity and relatively abundant local supplies. As Miller, Weatherford, and Thorson [1986] note, there appears to be remarkably little public concern in Southern California regarding salinity in water supplies [1990, p. 110].

In Chapter 5, we argue that information on appliances currently in use should be used in salinity damage studies. For now, note that none of the existing salinity damage studies have taken in-service appliances into account. However, survey-based studies of the service-life expectancy of household appliances and other durable consumer goods *without reference to salinity* <u>have</u> accounted for in-service units by using the life table that was developed for actuarial studies [Pennock and Jaeger, 1957, 1964; Ruffin and Tippet, 1975]. Studies of the life expectancy of household appliances employing the nonparametric product-limit method [Kaplan and Meier, 1958] or parametric maximum-likelihood methods [Nelson, 1982, p. 313] were not found. Parametric maximum-likelihood methods are used in accelerated testing, which we discuss in Chapter 5.

The literature review reveals many opportunities for improvement in the methods used for estimating benefits of salinity reduction. Technological changes and social changes (for example, in appliance ownership rates) in the years and decades since the earlier studies were produced have eroded much of the confidence the earlier studies may once have inspired. Several additional strands of relevant literature exist,

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[6] The citation corresponds to Miller and others [1986].

in applied statistics, in survey research, and in the consumer science field, little of which has yet been drawn upon for studies of residential damages from salinity. Salinity damage studies have focused on age of failure of previously owned appliances but have ignored the age of in-service appliances. The expected life of household appliances can be estimated from survey data of appliance age distributions and failure ages employing either the nonparametric product-limit method or parametric maximum-likelihood approaches [Kaplan and Meier, 1958; Nelson, 1982]. Survey design, including factors which encourage accurate responses and estimates such as questionnaire construction and sampling procedure, has also improved in recent years [Fowler, 1991]. We hope in this study to produce improved estimates of salinity damages to appliances.

CHAPTER 3

MINERAL CONCENTRATIONS IN ARKANSAS RIVER WATERS

This chapter takes up two topics relating to the salinity measures used in the study. First, we review the data on salinity in the River. The second section addresses the question of measuring impacts of individual ions.

ESTIMATES OF TAP WATER SALINITY IN THE ARKANSAS RIVER

We obtained salinity measurements for each water supply from the Colorado Department of Health.[7] The measurements were taken by the water utilities themselves or by contractors to the utilities. The salinity of water drawn from the river varies widely over the course of a year, as data from Pueblo demonstrate (Figure 1). Ground water is insulated to varying degrees from seasonal variations. Unfortunately, Pueblo's water utility is the only utility in the present study that makes frequent and regular measurements of salinity. For some utilities, only a few salinity measurements have ever been made. New Colorado state regulations (effective January 31, 1989) mandate salinity measurements as part of a corrosivity monitoring program.[8]

It is apparent from standard error estimates that substantial errors are likely in the estimated mean salinity levels for some water supplies (Table 1). Standard methods of fitting models require independent variables to be known exactly: the difference between the model and the measurements is assumed to be due solely to random errors or otherwise unexplained variations in the measurements of the dependent variable. When there is error in the independent variables of the model, the standard estimation techniques give inconsistent, that is, not asymptotically unbiased, estimates of the parameters. Therefore, parameter estimates presented in this study are bound to be at least a little biased. However, the range of salinity in the present study is large (a factor of more than 35). We are comforted, therefore, to observe that the likely error in any given salinity estimate is very small compared to the range of salinity covered by the measurements. We draw comfort also from the fact that three of the 13 salinity estimates are likely to be accurate to three percent or better and only four of them are likely to be in error by more than about 12 percent (Table 1).

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[7] In one case, Las Animas, one value was taken from a February 18, 1991 proposal by Environmental Engineering and Technology Corporation for a reverse-osmosis plant for the town.

[8] "The supplier shall collect samples. . .for the purpose of analysis of the corrosivity characteristics of the water. . .[including] Ph, calcium hardness, alkalinity, temperature, [and] total dissolved solids. . ." (Colorado Primary Drinking Water Regulations, Article 8, Colorado Department of Health, December 21, 1988).

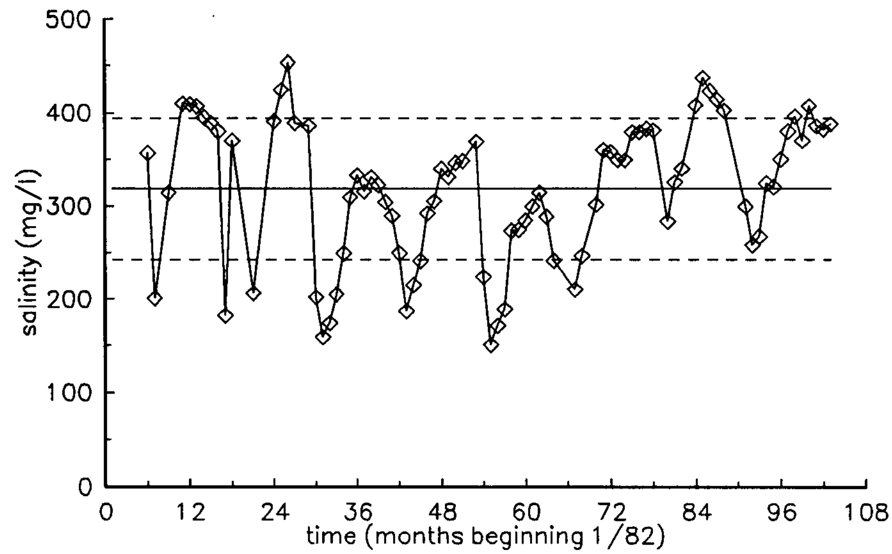

Figure 1. Salinity measurements and their sample standard deviation for Pueblo, Colorado (1982-1990).

It may be useful to check the accuracy of the salinity measurements performed by the utilities. One way to check the accuracy of the salinity estimates is to compare them with measured salinity levels of the river at or near the intakes to the water treatment plants. The comparison is strictly valid only for utilities using river water exclusively. To help assess the validity of such comparisons, we present (in Table 2) more detailed information obtained from the Colorado Department of Health on the utilities' water sources. Only Canon City, Florence, Pueblo West, and Pueblo use river water exclusively.

Salinity measurements for the Arkansas River at various points may be found in a report by Cain [1987, pp. 6-9, 37] (shown here in Table 3). Cain gives conductance measurements and conversion relations for conductance to total dissolved solids for the Arkansas river and some tributaries. Another source of data for checking the accuracy of the salinity estimates is data from the Colorado Department of Health [1971] (Table 3). The salinity data from the utilities roughly agrees with salinity data from the other sources (Table 3). Miles [1977] describes the geology of the Arkansas Valley and the salt loading of the river and performs mass balances for various ions over certain stretches of the river. He provides an explanation for the more rapid increase in sulfate concentration in the lower valley seen in the Health Department [1971] data. For the statistical models reported in the present report, we have used

Table 1 Summary of salinity data obtained from the Colorado Department of Health.

Water utility	Type[a]	Mean mg/l	SD mg/l	PSD %	SE mg/l	PSE %	n
Leadville[b]	s	142	55	39	25	18	5
Buena Vista	s	91	26	29	8	9	10
Salida	s	285	92	32	35	12	7
Park Center (Canon City)	g	957	244	26	141	15	3
Canon City	s	158	49	31	14	9	13
Florence	s	279	81	29	33	12	6
Pueblo West	s	343	116	34	58	17	4
Pueblo	s	319	76	24	8	3	83
St. Charles Mesa	s	451	100	22	36	8	8
Rocky Ford	s	988	203	21	91	9	5
La Junta	g	1253	33	3	17	1	4
Las Animas	g	3603	168	5	84	2	4
Lamar	g	1440	512	36	256	18	4

[a] Type (surface or groundwater), mean of n samples, SD (standard deviation), PSD (standard deviation as percentage of mean), SE (standard error of mean), PSE (standard error as percentage of mean).

[b] Parkville Water District.

the estimates derived from the data supplied by the utilities.[9]

[9] Note that Pueblo West, which takes its water from Pueblo Reservoir, apparently has higher salinity than does Pueblo, which takes its water from below the reservoir. If (1) the reservoir and the river are well mixed and (2) tributary flow between the two withdrawal points is at least as saline as the river or reservoir at the point where it joins the main flow, then the salinity within the reservoir ought to be no lower than at the point below its outlet where Pueblo draws its water. These provisos (1 and 2) are not established. In the absence of more data for Pueblo West, the best estimate now available is taken to be the one derived from the four measurements supplied by the utility.

Table 2 Detail on water sources for the utilities.

Utility	Detailed source information
Parkville (Leadville)	Canterbury Tunnel (groundwater) and Evans Reservoir (3 mi. east of town).
Buena Vista	Infiltration gallery (Cottonwood Creek) and three wells.
Salida	Arkansas River, Herrington Ditch, infiltration gallery (S. Arkansas), and infiltration gallery (Pasquale Springs).
Park Center (Canon City)	Artesian well, 3000 ft. deep.
Canon City	Arkansas River.
Florence	Arkansas River, Minnequa Canal.
Pueblo West	Pueblo Reservoir.
Pueblo	Arkansas River below reservoir.
St. Charles Mesa	Four wells east of Pueblo (55-60 ft. deep) and four wells above Bessemer Ditch via Bessemer Ditch.
Rocky Ford	Wells, Catlin Canal, and (April-October) Rocky Ford Ditch.
La Junta	Wells, 45 ft. deep.
Las Animas	Wells.
Lamar	Wells, 50-150 ft. deep in Clay Creek Aquifer. Recharged with Arkansas River water.

IMPACTS OF INDIVIDUAL IONS

Water-using appliances may suffer damage related to the concentrations of various ions. The major dissolved solids present in natural waters are given in Table 4 [Hem, 1989]. Chemical corrosion of metallic surfaces in contact with water cannot take place without electricity being conducted through the water [Smith, 1989, pp. 1-11]. The conductivity of water is approximately directly proportional to salinity, that is, the concentration of dissolved ionic solids [Walton, 1989]. Therefore, one might expect that the greater the salinity of a water, the greater its corrosivity [Obrecht and Myers, 1973, p. 80]. But DeBerry and others argue, in a comprehensive review of corrosion literature, that, at least in the case of iron, "Contrary to early predilections, solution conductivity itself has little effect on most modes of uniform or localized corrosion" [DeBerry and others, 1982, pp. 4-9]. The reviewers cite an instance in

Table 3 Comparison of salinity estimates from various sources.

Water utility	Salinity estimates (mg/l) from		
	utilities	river	1971 CDH
Leadville	142	152	113
Buena Vista	91	83	89
Salida	285	124	195
Park Center	957	-	880
Canon City	158	168	219
Florence	279	-	148
Pueblo West	343	-	-
Pueblo	319	377	531
St. Charles Mesa	451	-	751
Rocky Ford	988	-	1264
La Junta	1253	-	1953
Las Animas	3603	-	3075
Lamar	1440	-	597

which increases in conductivity of soft water by addition of NaCl lead to increased rates of corrosion of iron because of the formation of a less protective $Fe(OH)_2$ film (pp. 4-9). They also cite a study which reports that "an increase in conductivity may have the effect of actually promoting a more protective coating on iron in the presence of calcium carbonate film forming precursors" (pp. 4-10). Sulfate and chloride are reported to be the ions primarily responsible for the acceleration of corrosion [Obrecht and Myers, 1973, p. 80]. In water high in calcium and bicarbonate, an increase in temperature can cause the precipitation of calcium carbonate in the form of a scale that can inhibit corrosion [Obrecht and Myers, 1973, p. 78]. The concentrations of dissolved oxygen and carbon dioxide have an important effect on the corrosivity and scale forming potential of a water [Obrecht and Myers, 1973, pp. 80-81].

It seems that the composition of a water is so important to its ability to damage appliances that knowing the salinity is not enough: the effects of each ion and

Table 4 Major ionic constituents of natural waters.

Cations	Anions
Calcium (Ca^{2+})	Sulfate (SO_4^{2-})
Magnesium (Mg^{2+})	Chloride (Cl^-)
Sodium (Na^+)	Fluoride (F^-)
Potassium (K^+)	Nitrate (NO_3^-)
	Bicarbonate (HCO_3^-)
	Carbonate (CO_3^{2-})

dissolved oxygen and carbon dioxide must be accounted for individually. However, if the correlations between the concentrations of various constituents are high, it may not be possible statistically to make a separate accounting. The concentrations of the major ions in the drinking water of the Arkansas Valley of Colorado are highly correlated (Figure 2) [Colorado Department of Health, 1971]. A semi-log scale, for which equal vertical distances represent equal proportions, gives a better picture of the approximately constant proportional mixture (Figure 3). Sulfate is an exception to the rule between Florence (about 125 miles from Leadville) and Rocky Ford (a little over 200 miles from Leadville). Calcium- and sodium-sulfate bearing soils under agricultural irrigation load the river with sulfate in much of that stretch [Cain, 1977, pp. 31, 39].

The water utilities represented in Figure 2 and Figure 3 correspond to, in order of distance from Leadville: Leadville (Parkville Water District), Buena Vista, Salida, Canon City, Florence, Pueblo, St. Charles Mesa Water District, Rocky Ford, La Junta, Las Animas, and Lamar.[10] The estimated correlation coefficients between the concentrations of hardness (the concentration of multivalent cations, mostly calcium and magnesium), sulfate, chloride, and total dissolved solids for the municipalities listed above indicate high correlations between the various ions (Table 5). Due to the high correlations, there appears to be no hope of distinguishing statistically the effects of various ions in the waters of the Arkansas Valley.

Is this a serious problem? What would we do with the information on the effects of different ions if we had it? Would we propose to remove only certain ions? Water utilities and households often remove the ions responsible for hardness. But other options for relieving salinity problems would reduce the concentrations of each ion by about the same proportion. For example, the Bureau of Reclamation proposed a pipeline as a part of the Fryingpan-Arkansas Project that would transmit water of

[10] This list is the same as the list of water utilities included in our 1991 survey except for the omission here of Pueblo West and Park Center in Canon City.

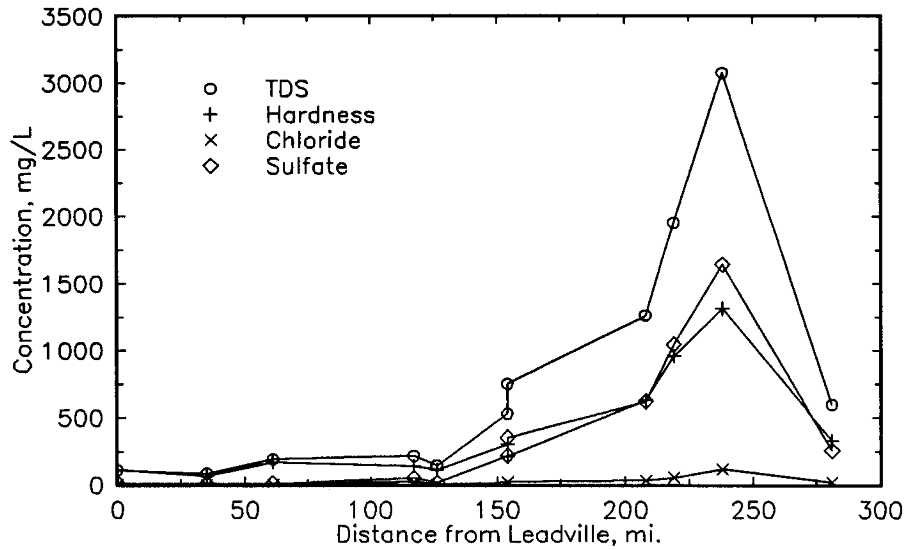

Figure 2. Concentrations of various constituents in the waters of selected water utilities in the Arkansas Valley.

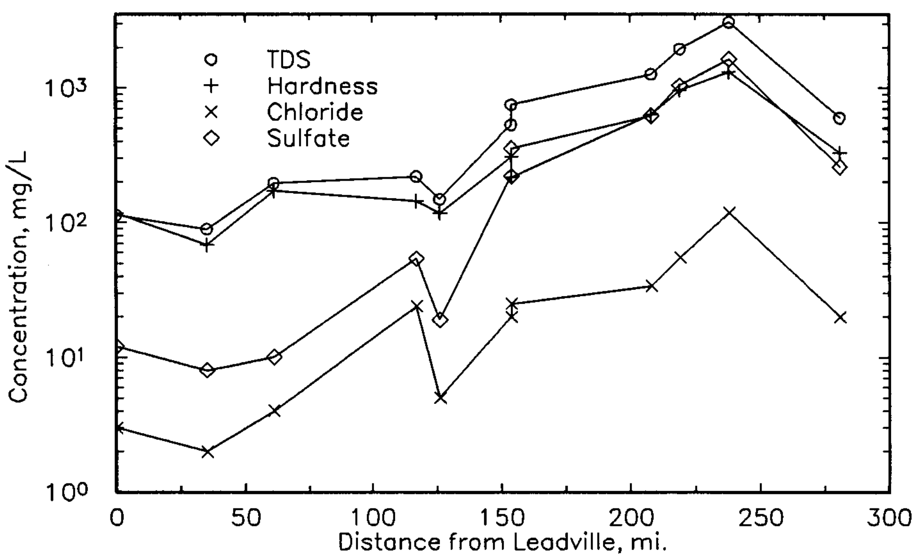

Figure 3. Semi-log plot of concentrations of various constituents in the waters of selected water utilities in the Arkansas Valley.

relatively low salinity from Pueblo reservoir to communities in the plains [Black & Veatch, 1972; Cress, 1989]. Because the proportional mixture of ions is fairly constant

Table 5 Correlation coefficients, in percentage, between various water quality measures for selected water utilities of the Arkansas valley.

	Hardness	Sulfate	Chloride
TDS	98.84	99.95	97.02
Hardness		98.74	94.54
Sulfate			96.89

along the river, the pipeline would reduce by approximately the same proportion the concentrations of most ions; therefore knowledge of the economic benefit of the pipeline does not depend on knowledge about the particular effects of the various ions.

An unfortunate, but in this case unavoidable consequence of ignoring the particular effects of individual ions is that, to the extent that the relative proportions of the various ions matter, the conclusions of a study involving a particular relative proportion of ions will be less accurate for water with a different proportional mixture of ions.

CHAPTER 4

DATA COLLECTION

For the purposes of the study, it was necessary to obtain data from households that would describe practices and experiences related to consumption of water, water-using appliances, and household plumbing. Data from households were obtained using a cross-sectional survey. These are usually less expensive to conduct than longitudinal surveys and make it possible to obtain data from a larger and more representative sample in a short period of time. The mail survey included three questionnaires targeted to households, appliance repair firms, and plumbing firms along the Arkansas River. Two criteria for choosing the targeted groups were used as the basis for developing the samples: (1) homogeneity in the group selected—households' using water from the Arkansas River basin; and (2) common interests or problems. Households, plumbers, and appliance repairers all have experience with water-using appliances, plumbing, and related costs. Plumbing firms and appliance repair firms deal with water quality and its consequences as they do a portion of their business with households. Because of the variation in water quality along the River, mail questionnaires were distributed to these three groups to gain an understanding of the effects of varying levels of minerals in water.

This chapter presents the background for selecting and using a cross-sectional survey and the detailed descriptions of the questionnaires' design. The sampling, mailing procedures, and response rates are discussed in the last section of the chapter.

MAIL SURVEYS

In developing the mail survey, four major factors were addressed [Gorton & Carr, 1983]. These were (1) identification of the survey and (2) the respondents. In designing the questionnaire, (3) control and (4) survey questions were developed to assure valid and reliable results.

To give the survey a distinctive and consistent identification, the questionnaires were labeled with a title which was also used in the cover letters. The identification and the conditions of the research (e.g., time, purpose, etc.) were communicated to potential respondents in the cover letters. A graphic on the questionnaires' covers and other mailings furthered the distinctive identification. To identify the respondents' characteristics related to the research objectives, both housing and socioeconomic variables were included in this section. Similarly the appliance repair and plumbing firms were described.

Control questions were designed to determine whether or not respondents were giving consistent answers (perception of water quality and actual practices). These were also used to determine whether the instructions for completing the questionnaire were followed in the pilot test. A common device for control questions is asking questions twice in different parts of the questionnaire to get similar information (e.g., zip code from respondent to match to that on mailing address).

Survey questions are the major part of the questionnaire (see Appendix 2) and require most attention. There are four main question types [Gorton & Carr, 1983]: (1) simple dichotomous questions—designed to be answered in only one of two possible ways (i.e., Q. 31 - gender); (2) multi-choice questions—respondents choose from a range of possible answers (i.e., Q. 33 - family income category); (3) open-ended questions—call for a wide variety of response (i.e., Q. 26 - As you circled $58 per month, this was because—this question assessed respondents' attributes to water quality); and (4) scaling questions—used to determine the views of the respondents as to the attributes of a particular product (i.e. Q. 3 - Describe the quality of water in your home. The respondents are asked to rate each attribute on a five-point scale from rusty to no rust).

Questionnaire design must be matched to respondent characteristics and interest. In addition to cover letter content, questionnaire length and instructions are important for optimizing quantity and quality of responses. The length of questionnaire should consider the time factor for completion by respondents. Some researchers suggest six to eight pages of questions are about right [Vichas, 1982]. The Total Design Method (TDM) indicates that a questionnaire of less than 12 pages is reasonable; however, if it is beyond 12 pages, response rate reductions can be expected [Dillman, 1978]. In this study the final questionnaire contained 13 pages of questions for households. A single question was on the last page (13).

An important part of a mail questionnaire is to ensure that the instructions for its completion are clear and unambiguous. Respondents must know how they are expected to respond: with a check, a circle, or by writing in their response and which questions to skip if not applicable. In the water questionnaire, instructions were repeated and illustrated in each question.

HOUSEHOLD CONSUMPTION STUDIES

In developing the survey questions, the characteristics of consumption behavior were considered. Household variations due to several factors—timing, consumption patterns between and within households, product variability, and sensitivity to questions [Magrabi, et al., 1991]—were considered in question development.

For consumption data, the time when data are collected needs to be considered in evaluating results. For example, water is used daily but appliance repair is infrequent. Further, for household water-using appliances, consumption pattern variations may be needed to improve the accuracy of respondents' recall as households do not have similar use, ownership, or repair experiences. Careful definitions of what is included in price for replacement or repair are needed, and questions and their response categories need to take into account household variations. Some appliances, as washers, may be primarily used by one individual in the household; other items (shower) are used by all household members although not necessarily equally. Therefore, it was assumed that household members could jointly complete the questionnaire or the person with the most knowledge would complete the relevant sections.

Most appliances are highly variable in saturation, quality, and features. For example, the portion of homes with water heaters differs from the portion with humidifiers. Further within the same product class, quality, size, and other specifications distinguish one model from another and/or brand.

Consumers are more willing to provide information and be more honest in their responses for some variables than others. For example, data on income and assets are less likely to be reported and when reported are more likely to be underreported.

DATA BEST COLLECTED WITH MAIL SURVEYS

A distinction should be made among three types of variables used as measures of household consumption of goods and services: acquisition, purchase, and use [Magrabi, et al., 1991]. Each type of variable may be measured in terms of quantities of goods and services (how many or how much more or less) or in terms of monetary value (cost). Both were done in this study. Data on these types of variables are best collected through a mail questionnaire because these questions usually take time to answer. Likewise, in this water study, a relatively large amount of data was needed. A mail survey allows respondents to think about or consult records if they chose, as respondents do not have to recall instantaneously.

As with any methodology, mail surveys have advantages and disadvantages. Advantages relate to ease of increased sampling both in numbers and geographic dispersion of potential respondents. Disadvantages relate to response rates and time. Some advantages and disadvantages are listed here as they were the basis for choice of data collection.

Advantages

1. The mail survey achieves a width of distribution. Respondents in outlying areas and all sizes of communities can be contacted as easily as those in larger population area [Kress, 1982].

2. The mail survey eliminates interviewer bias [Gorton & Carr, 1983]. Respondents are not influenced by the presence or voice of an interviewer. Because respondents remain anonymous, they are also more willing to answer somewhat personal questions.
3. The mail survey may get more accurate and thoughtful replies. Respondents have the option to proceed at their own pace, giving thought to their responses and/or looking up records.
4. It is less expensive to obtain information, especially when potential respondents are spread over a wide geographic area, using a mail survey than telephone or in-person interviews.

Disadvantages

1. There may be greater nonresponse with mail surveys than with other methods. A question arises as to whether respondents are representative of the universe under study. In this study an abbreviated postcard survey of nonrespondents was used to compare respondents and nonrespondents.
2. The length of questionnaire is a limitation for the survey. There tends to be an inverse relationship between the length of the questionnaire and the percentage of responses to it. A questionnaire exceeding 12 pages usually lowers response rates [Dillman, 1978].
3. It can take anywhere from two to four weeks before a majority of the returns are received. If follow-up letters are used, the return period is further lengthened. Though this slows completion of a study, duration is less of a concern in a study of water quality because intervening events do not unduly influence earlier or later responses as they would with a topic including current political views.

PERSONAL INTERVIEWS AND TELEPHONE SURVEYS

Information can also be obtained from consumers by personal and telephone interviews. Each is labor intensive, depends on access to potential respondents, and increases in cost as larger or more diverse geographic areas are included. Attributes of personal and telephone interviews are explored to point out their characteristics in view of mail survey's suitability for this study.

Personal interviews

1. A wide range of questions can be covered if an interview is lengthy. The interviewer may be able to use more questions if subjects are not constrained by time [Gorton & Carr, 1983]. In today's busy world, many people are not willing to be subjected to lengthy interviews.

2. Interviewers can validate answers by observation or continual probing. The interview can be managed effectively and be directional based on responses.
3. Personal interview studies often claim a more acceptable response rate, with a low refusal rate. This may be related to how refusals and non-availables are counted and interpreted.

Telephone surveys

1. Costs are especially low when the survey is limited to a local calling area. A wide geographical spread cannot be covered as inexpensively.
2. Travel time between interviews is not needed, nor is time lost waiting for return of questionnaires. Yet, efficiency depends on availability of respondents without repeated callbacks.

QUESTIONNAIRES USED IN ARKANSAS BASIN STUDY

Three questionnaires (see Appendix 2) were developed to survey each: households (consumers), appliance repairers, and plumbers. As the data from each were to provide specific information, the three are individually described. A fourth questionnaire was developed to survey nonrespondent households.

Household questionnaire

The household questionnaire was titled "Water in Your Community: Quality and Costs." It was formatted as a booklet (7" x 8½") with a graphic, the title, and a message of encouragement to respond and appreciation for response on the cover. The 16-page booklet was printed black on white.

The questionnaire was divided into nine titled sections: (1) Water; (2) Around Home; (3) Your Water-Using Appliances; (4) Household Fixtures and Plumbing; (5) Laundry; (6) Your Car/Truck; (7) Bottled Water; (8) Value of Improved Water; and (9) You, Your Family, and Your Home. Each section sought information relevant to the quality of the household's water supply, the direct and indirect costs of that water and its use, and demographic data on the respondent. The blank back cover (both sides) allowed for respondent's written comments on water quality.

Water. The first section included three questions. They were structured to be easy to respond to as an effective lead into the questionnaire. The first asked for one of four ratings (from excellent to poor) of water quality in the local area (Q-1). Next, respondents were asked to indicate water quality change over the last three years (Q-2). Question three used a five-point semantic differential scale with eight bipolar characteristics to describe the household's water quality. The characteristics included clarity, hardness, smell, and taste. The remaining four characteristics determined whether the water supply caused stains/discoloration, filming, scaling, and its mineral content.

Around home. Two questions were developed to ascertain the effect of the household's water supply on household activities and equipment. In question four respondents were asked to indicate whether the water caused discoloring or pitting of pots and pans, coffeemakers, and teakettles. Five items explored the effects of water quality on clothes (laundry), on fixtures (tubs/showers, toilets, etc.), and dishes. The last section asked if water caused problems in seven items (e.g., steam irons, aquariums, auto batteries). It was recognized that households may not have all of these items. In addition, respondents could add "other" items they owned/used which had water caused problems.

Because water quality can affect the difficulty of work around the home, respondents were asked if they spend extra hours per week (none, < 1, 1-3, or > 3) doing four groups of household work—cleaning, laundry, water treatment equipment maintenance, and meal preparation and clean-up (Q-5).

Your water-using appliances. To determine appliance dependability and service life, two questions were asked in relation to the repair (Q-6) and replacement (Q-7) of each of eight water-using appliances. The appliances were water heater, clothes washer, dishwasher, water softener, other water treatment unit, humidifier, garbage disposer, and evaporative (swamp) cooler. The eight appliances were ordered and grouped in relation to current saturation levels. Humidifiers and evaporative coolers were included because of the dry winter and dry and warm summer of Southern Colorado. For each appliance, respondents were asked to provide its age and if repaired—the year, nature, and cost (unless under warranty). For appliances replaced or added (Q-7), the age of the appliance replaced, year of acquisition, and details of service contract (cost, duration, and usage), if purchased, were asked for each.

Household fixtures and plumbing. This section sought information on service life and cost of fixtures and plumbing for kitchen, bath, and laundry, as well as water supply and wastewater plumbing and water treatment equipment. The first question in the section (Q-8) explored replacement, service life, and costs of 11 kitchen and bath features exposed to water. These included each of the fixtures (e.g., kitchen sink, bathtub) and their faucets and/or mechanisms. Respondents could add additional items for other baths and/or fixtures.

Questions nine and ten, respectively, ascertained the materials (plastic, copper, etc.) of water supply and wastewater piping, when replaced (year), replacement cost, and material(s) of replacement. The last question (Q-11) of this section identified the presence or absence of water treatment units and the associated monthly costs. The most common and most aggressively marketed types of units—softeners, filters, reverse osmosis—were included.

Laundry. To acquire data useful in determining amounts of laundry (loads) and costs, household respondents were asked to indicate number of loads done weekly at laundromats (Q-12) and at home (Q-13). In addition, respondents were asked if they used more, less, or the same amounts of detergent as stated in the instructions and if more or less, the quantity (Q-14). Type of laundry products used (detergent in combination with bleach, softener; water softener) and whether each was liquid or powdered were also included (Q-15).

Your car/truck. Water quality can have an effect on the life of an automobile's cooling system and battery. Therefore, respondents were asked for automobile age and cost of any cooling system repairs (Q-16) for up to three vehicles. They were also asked the cooling system mixture usually used (Q-17). Information on water usage in batteries was included in Q-4.

Bottled water. With increasing sales of bottled water and its possible use as a substitute for poor quality water, respondents were asked if they used bottled water and their weekly cost (Q-18). Additional items in the question asked for bottled water uses, quantities used weekly, and reasons for use. Other beverage substitutes for tap water and related weekly expenditures were also asked (Q-19).

Value of improved water. This section was developed consistent with contingent valuation methods to ascertain interest in improved water quality (lowered mineral content) and the amount per month respondents would be willing to spend (two dollar increments from zero to 58). Reasons for willingness to spend zero (Q-22) or the maximum (Q-23) in the range were also asked. Similarly respondents were asked to indicate willingness to pay for improved water quality to lessen indirect costs (i.e., inconvenience, more work) (Q-24). Again reasons for willingness to spend zero (Q-25) or the maximum (Q-26) were explored with open-ended questions.

You, your family, and your home. The final section explored respondent's demographic and housing related characteristics. Included in Q-27 were number of persons in household, type of housing unit, tenure, and source of water (community system, well, etc.). Years in present home (Q-28) and age of home (Q-29) were asked to assist in interpreting service life related variables. Zip codes—current and former—were asked to match to water district and length of time in area. Personal demographics included gender (Q-31), education level (Q-32), and 1990 total family income (Q-33).

Appliance repair questionnaire

The appliance repair questionnaire was titled "Water in Your Community: Appliances." It was designed as a booklet (7" x 8½") with the same cover graphic as the consumer questionnaire but with a slightly different message expressing encouragement and appreciation for response (Appendix 2). The eight-page booklet was printed black on white. The back cover (both sides) allowed for comments.

The questionnaire was divided into three sections. These included Water in Your Community; Appliance Repair Histories; and Service Lives of Appliances. An introductory question asked the respondent to indicate number of years the firm had been doing business in the community (Q-1).

Water in your community. The first section included four questions related to the community's water supply. These included water quality (Q-2) and its change if any in the last three years (Q-3). A three-item semantic differential asked for a description of the effect of water on appliances and plumbing (Q-4). Lastly, repairers were asked to estimate the percentage of their customer base on private wells (Q-5). These questions were the same as those included in the plumbing questionnaire (Q-2, Q-3, Q-4, and Q-5).

Appliance repair histories. To determine water-related repairs for six water-using appliances—dishwashers, clothes washers, gas water heaters, electric water heaters, garbage disposers, and evaporative coolers—repairers were asked to indicate the most frequent cause of repairs (corrosion, scaling, mechanical, electrical, or other) for each (Q-6). In addition respondents were to estimate the number of repair calls during the service life of each of the appliances and the average cost of typical service calls (Q-7).

Note that households were asked about humidifiers and water treatment units. These were not included in this questionnaire as humidifiers are usually considered small not major appliances for repair purposes. Water treatment units are usually serviced by specific suppliers rather than general appliance repairers.

Service lives of appliances. To determine service life, repairers were asked to indicate the most frequent cause of replacement for each of six water-using appliances (Q-8) and to indicate average age of appliances replaced (Q-9). Due to the fact that water heater life is related to the sacrificial anodes and a suspicion that some firms remove anodes in an effort to reduce the odor associated with the magnesium anodes and sulfate containing water, specific questions were asked related to removal and replacement of these anodes (Q-10). Service life of heating elements in electric water heaters and the prevalence of electric heaters were also asked (Q-11).

Residential plumbing questionnaire

The questionnaire directed to plumbers was titled "Water in Your Community: Residential Plumbing." It was designed as a booklet (7" x 8½") with the same cover graphic as the consumer questionnaire and a targeted message expressing encouragement and appreciation for response (Appendix 2). The eight-page booklet was printed black on white. The back cover (single side) allowed for comments.

The questionnaire was divided into four sections—Water in Your Community; Potable Water Piping; Wastewater Piping; and Fixtures and Appliances. An introductory question asked the respondent to indicate number of years the plumbing firm had been doing business in the community (Q-1).

Water in your community. The first section included four questions related to the community's water supply. These included the quality (Q-2) and its change in the last three years (Q-3). A three-item semantic differential asked for a description of the effect of water on appliances and plumbing (Q-4). Lastly plumbers were asked to estimate the percentage of their customer base on private wells (Q-5). This section was the same as that included in the appliance repair questionnaire (Q-2, Q-3, Q-4, and Q-5).

Potable water piping. Questions were developed to determine the piping material(s) used in water systems (Q-8.2) and the percentage of the firm's jobs using each type for replacement (Q-8.1). The age at time of replacement (Q-6.1) and the average cost (Q-6.2) for each of the types—galvanized steel, copper, plastic, and other—were asked. To gain further information on service life, number of repairs expected during the service life of a system and average repair costs for each material type were included (Q-7).

Wastewater piping. Similar questions were asked for the wastewater system as for the water system. For wastewater systems, cast iron was also included as one of the pipe materials. Question nine asked age and cost of replacement and Q-10 requested number of expected repairs and average cost by material type. The last question in the section (Q-11) asked for frequency of use of each material when pipes are replaced and the percentage of homes with each type of piping.

Fixtures and appliances. Plumbers were asked to indicate age at replacement of 16 items including faucets/shower heads by material and placement (e.g., kitchen, bath sink), fixtures (e.g., sink, toilet), water heaters, and lawn sprinkler systems (Q-12). In addition they were asked to write in other water-using fixtures.

Due to the fact that water heater life is related to the sacrificial anodes and a suspicion that some firms remove anodes in an effort to reduce the odor associated the magnesium anodes and sulfate containing water, specific questions were asked related to removal and replacement of these anodes (Q-13). Questions regarding the service life of heating elements in electric water heaters and the prevalence of electric heaters were also asked (Q-14).

Household nonresponse questionnaire

To examine whether household nonrespondents were similar to or different from respondents, a four-panel postcard questionnaire (see Appendix 2) was developed. The black on yellow bifold card (6" x 9" unfolded) was formatted with a brief introductory message and the same graphic used on the questionnaires on one panel backed by the respondent address panel. The questions were on the lower panel backed by the return address panel (with return postage). Respondents could either refold the card with the return address panel to the outside and mail it or detach their address and the message (upper panel) and mail the question/return address panel (lower panel).

Unnumbered questions (to conserve space) asked for rating local water quality from excellent to poor. A question asked for repairs and their costs for water-using appliances and replacements in the last two years. Another question asked for the piping material used in the water system. A Yes/No response question inquired if the mineral content of the tap water should be reduced. Source of household water (city/town, well, etc.) was to be identified. Demographics included household size, years in present home, zip code, and highest level of education of the respondent.

SAMPLING, QUESTIONNAIRE DISPOSITION, AND RESPONSE RATE

The sample was chosen from six Colorado telephone directory white pages which included Leadville (November 1990 edition); Buena Vista and Salida (April 1990 edition); Canon City and Florence (April 1990 edition); Pueblo (March 1991 edition); Rocky Ford, La Junta, and Las Animas (April 1991 edition); and Lamar (April 1991 edition). The telephone directories used were the most recent editions available. The sample of 2,226 included households of ten cities located along the Arkansas River in Colorado (Table 6).

Table 6 Sampling frame

City	Households estimate (total)	Mail out (#)
Leadville	2,057	105
Buena Vista	1,894	269
Salida	2,799	65
Canon City	6,835	363
Florence	1,527	34
Pueblo	32,038	650
Rocky Ford	1,740	99
La Junta	3,181	188
Las Animas	1,189	246
Lamar	3,960	207
Total mail out		2,226

After estimating number of households in each directory, comparing to Census data, and determining adequate sample size to allow comparisons by TDS levels, sample selection was done by counting every 20th household in La Junta, Lamar, Rocky Ford, and Leadville; every 50th household in Salida, Florence, and Pueblo; every 25th household in Canon City; and every fifth household in Las Animas. If the *i*th name was a business, selection was alternated between the preceding and succeeding name.

For the appliance repair and plumbing firms, all those listed under appliance repair, plumbing, or related titles in the yellow pages were included in the sample. Exceptions were companies recognized as selling products but not providing repair services.

Mail-out procedure

In late July 1991, a questionnaire, cover letter, and return stamped envelope were mailed first class to the sample of 2,226. An identification number was stamped on the front of each questionnaire to facilitate follow-up efforts.

Follow-up postcards were sent to the sample eleven days after the original mailing. Postcards were sent to all who received first mailings except those who already responded, returned undeliverable, deceased, and noted no forwarding address. In early September, the same questionnaire with a new letter, using the same procedure as the first mailing, was sent to those who had not returned the questionnaire. This mailing was not sent to anyone whose first questionnaire or postcard had been returned undeliverable for whatever reason.

At the same time, two different questionnaires were distributed to appliances repair firms and plumbing firms in these same communities. For repair data, questionnaires were sent to 65 appliance repair firms and 73 plumbing firms.

After data collection ended (October 27, 1991), response rates for each of the three water quality questionnaires were calculated (Table 7).

Table 7 Water Quality Questionnaire Disposition and Response Rates.

	Residential	Appliance	Plumbing
		(number)	
Questionnaires sent	2,226	65	73
Questionnaire disposition			
usable returns	872	21	19
overt refusals	97	6	5
ineligible (deceased, no longer in business, moved local)	19	15	16
could not locate (undeliverable)	220	5	5
Response rates		(percent)	
usable of total sent less ineligible and undeliverable	43.9	46.7	36.5
usable of total sent	39.2	32.3	26.0

Of the 2,226 household questionnaires, 872 questionnaires were returned and usable, 97 were overt refusals, 19 ineligible due to moves, death, etc., and 220 were undeliverable. The response rate was 44 percent when ineligible and undeliverable were excluded.

The household response rates by community are shown on Table 8. Among ten communities, Buena Vista had the highest response rate with 70 percent, while Florence had the lowest response rate with 29 percent.

Table 8 Response rates by community

Community	Mailed	Ineligible/ undeliverable	Responses returned	Rate
		(number)		(percent)
Leadville	105	34	29	40.8
Buena Vista	269	52	152	70.0
Canon City	363	51	108	34.6
Salida	65	24	24	47.1
Florence	34	6	8	28.6
Pueblo	650	30	249	40.2
Rocky Ford	99	7	39	42.4
La Junta	188	11	80	45.2
Lamar	207	24	80	43.7
Las Animas	246	10	103	43.6
Total	2,226	239	872	43.6

Of 65 questionnaires sent to appliance repair firms, 21 were usable. The response rate was 32 percent. Plumbing questionnaires were mailed to 73 firms; 19 questionnaires were usable. The response rate was 26 percent.

CHAPTER 5

IMPROVED METHODS FOR ESTIMATING APPLIANCE REPLACEMENT COST

Great improvements could be made in salinity damage estimates by using some of the methods of data reduction used in previous salinity damage studies with recently and carefully collected data. In part, that is what we hope to accomplish. However, some of the methods used in previous studies may give biased estimates of salinity damage. We suggest two ways to eliminate at least some of the bias that results from using the methods used in previous studies. The first suggestion, while already employed in some previous salinity damage studies, was put on firmer theoretical footing by Booker [1990, pp. 102-105]. A more general justification for the method he proposes for reckoning appliance replacement cost is provided. The second suggestion is to properly account for the ages of in-service appliances.

THE RECKONING OF APPLIANCE REPLACEMENT COST

In one previous salinity damage study, d'Arge and Eubanks [1978, p. 263] calculate the present value of a strictly periodic stream of replacement expenditures: the period being equal to the expected value of the failure time:[11]

$$\sum_{i=1}^{\infty} [A/(1 + r)^{i\mu}] = A/[(1 + r)^{\mu} - 1] , \qquad (1)$$

(6)where A is the constant price of a replacement, r is the simple annual real discount rate, and μ is an estimate of the expected life of an appliance. The present value formula implies an equivalent perpetual annual payment of

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[11] D'Arge and Eubanks do not take the sum to infinity, but truncate the expression at 60 years in an attempt to account for the finite life of housing units. If we assume that worn out houses will be replaced by new ones and that the owners will equip their homes with new or used appliances, either moving their old ones into their new houses or buying new or used ones, then the life of houses is irrelevant to the cost of salinity damage to appliances. On the contrary, ignoring appliance replacements that might occur after 60 years is consistent with assuming a population that vanishes in 60 years. Taking the sum to infinity is consistent with assuming that population is constant. One could easily adjust the estimates generated on the assumption of a constant population to a stipulated growth rate. On the other hand, the entire issue is likely to be unimportant because, at a discount rate of more than a few percent, the cost contribution from units purchased more than 60 years in the future will be negligible.

$$A/r[(1 + r)^{\mu} - 1] \; . \tag{2}$$

Certain other studies have used a capital recovery factor for the initial expenditure (ignore, for the moment, future replacements) to calculate a uniform annual payment to be made over the expected life of the appliance [Black and Veatch, 1967, pp. 12, 32; Tihansky, 1974, p. 148]:[12]

$$Ar(1 + r)^{\mu}/[(1 + r)^{\mu} - 1] \; . \tag{3}$$

The payment is assumed to continue forever to pay off future replacements. In practice, (2) and (3) are equivalent because the factor of $(1 + r)^{\mu}$ difference between the two is due to different assumptions about when the stream of replacement expenditures begins. Equation (2) is based on the assumption that the first expenditure takes place after one average life. Equation (3) is based on the assumption that the first replacement expenditure takes place at time zero. The expenditure at time zero cancels out when, to find the cost of salinity damage to the appliance, the appliance replacement cost at zero salinity (or at some other level) is subtracted from the cost at the salinity level in question.

Some other salinity damage studies ignore discounting and calculate annual cost by dividing the price of a new appliance by its expected life [Coe, 1982, p. 60; Lohman and others, 1988, p. 42; Metcalf & Eddy, 1972, p. 31]. Booker [1990, pp. 102-105] shows that such a practice is consistent with assuming a uniform age distribution of appliances whose lifetimes are identically equal to the expected lifetime. Booker also shows that calculating replacement cost by discounting a stream of future payments starting at time zero or at the end of the first lifetime implicitly assumes that all appliances are new at the time the salinity changes.

The key to the independence of aggregate appliance replacement cost on the discount rate is the assumption of a steady state in which the number of appliances replaced each year is constant [Booker, 1990, p. 105]. Following Ragan [1992], we will derive the steady-state age distribution that could arise under more realistic age distributions that would result from failure time distributions in which appliances fail at random times.

Booker [1990, p. 106] presents estimates of replacement cost under both the "uniform distribution" assumption and the "all new" assumption. The two alternative assumptions are polar in the sense that in one case the full benefit is assumed to arrive

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[12] Tihansky's paper has a typographical error in its version of this equation. The report produced by Black & Veatch uses the equation shown here but computes the cost for separate surveys by taking the life of the previous appliance unit to be the expected life, unless no such life was reported, in which case they take the average of reported lifetimes for the community.

immediately and in the other case no benefit is noticed until the appliances would have been due to fail under the old salinity level. It is instructive that there is not much difference in Booker's alternative replacement cost estimates for a change in salinity from 500 to 600 mg/l under the two polar assumptions, except for very long-lived items such as water pipes [Booker, 1990, p. 106]. The largest difference evident for appliances is about five percent for clothes washers.

Booker shows that previous studies that use the present value of a stream of future payments to estimate appliance replacement cost implicitly assume an initial age distribution for which all appliances are new when salinity changes. As a byproduct of a general treatment of appliance replacement cost, Ragan [1992] shows, and we reproduce below, that previous studies only approximate the correct answer for the case where all appliances are initially new. Another byproduct, Booker's result that the appliance cost is independent of the discount rate for a steady-state uniform age distribution, emerges as a special case. Finally, we see that Booker's result holds for any steady-state age distribution.

Householders replace appliances for various reasons. A working clothes washer might be replaced because newer models have features that the householder considers to be worth the extra expenditure. A water heater might be replaced because the tank rusts through. In any case, the exact time of the replacement expenditure is not known in advance. Therefore, the present value of the cost of all future replacements of an appliance is the expected present value of a stream of randomly timed replacement expenditures. As we have seen, all previous salinity damage studies have assumed instead a strictly periodic stream of replacement expenditures.

Assuming a neutral attitude toward risk, the qualitative difference in cost between a strictly periodic stream and a randomly timed stream of appliance replacements is the same as the difference between the values of two alternative prizes: the promise to be paid $10,000 exactly ten years from now, and a promise to be paid $10,000 at a future time determined randomly from a probability distribution having ten years as its mean. If the discount rate is zero, then there is obviously no difference between the values of the two alternative prizes. But at ten percent discount, say, one would prefer to avoid a delay of a few months or years. Payment before ten years would, of course, be welcome.

A systematic way to choose between the two would be to compare present values. In one case, the sure thing, we have the present value of $10,000 to be paid ten years from now. In the other, the gamble, we have the expected value of the present value of $10,000 that will be made at some random time in the future whose expected value is ten years from now. The Jensen Inequality can be used to prove that the expected present value of the gamble is greater than or equal to the present value of the sure thing: you gain more by being paid a year early than you lose by being paid a year late.[13]

We may regard the usual approximation, represented by (2) or (3), as a first approximation to the exact result under the assumption that all appliances are new when salinity changes. To obtain the exact result we must account for the random timing. To show that an initial steady-state uniform age distribution implies an annual cost or benefit of salinity change that is approximately independent of the discount rate, we will introduce the initial age explicitly.

An appliance of age τ_0 is subjected to a change in salinity such that the expected life of a new unit changes from μ_0 to μ. Assume a transformation that converts the actual age τ_0 to the effective age $\tau = (\mu/\mu_0)\tau_0$ under the new salinity level. The implied model is the same as the accelerated-testing model to be introduced later. The first failure under the new salinity level would, according to the model, occur at a time reduced by the effective age: $t_1 - (\mu/\mu_0)\tau_0$. As an illustration of the model, consider a case in which the expected life of a new unit doubles from five to ten years. The expected time of the first failure is $E[t_1 - (10/5)\tau_0] = 10 - 2\tau_0$. If the actual age was four years, the effective age would be eight years and the expected time of failure would be two years hence. The expected remaining life doubled from one to two years.

The expected present value of an infinite stream of randomly timed future payments, adjusting the first failure to the effective age, may be written as follows:

$$\begin{aligned} E[P] &= E[A\textstyle\sum_{j=1}^{\infty} \exp(-\rho((\sum_{k=1}^{j} t_k) - \tau_0\mu/\mu_0))] \\ &= E[A\textstyle\sum_{j=1}^{\infty} \prod_{k=1}^{j} \exp(-\rho t_k)\exp(\rho\tau_0\mu/\mu_0)] \\ &= E[A\exp(\rho\tau_0\mu/\mu_0)\textstyle\sum_{j=1}^{\infty} \prod_{k=1}^{j} \exp(-\rho t_k)] \end{aligned} \tag{4}$$

where A is the assumed constant price of the appliance, $\rho = \ln(1 + r)$ is the continuously compounded real discount rate, and t_k is the failure time (actual service life) of the kth appliance purchased. Some previous salinity damage studies have

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[13] The Jensen Inequality: "Let X be a random variable with mean $E[X]$, and let $g(\circ)$ be a convex function [from below]; then $E[g(X)] \geq g(E[X])$" [Mood and others, 1974, p. 72]. The present value function, call it $g(\circ)$, is a decaying exponential which gives the present value of \$10,000 as a function of time. It is convex as required. Therefore, the present value of the sure thing, $g(E[X]) = g(10)$, is less than or equal to the expected value of the present value of the gamble, $E[g(X)]$.

implicitly approximated (4) by taking $\tau_0 = 0$ and substituting the estimated mean failure time, μ, for the random variables t_k.[14]

Assume that the t_k in (4) are independent random variables drawn from the same distribution. The exponential functions under the product sign in (4) are functions of the independent variables and are independent of each other. The initial age is so far a constant and, like A, can be moved across the expectation operator. Now, allow the initial age to be a random variable independent of the failure time variables. The expected value of a product of independent random variables is the product of the expected values. The expectation operator can therefore be moved across the product sign and the expectation of the function of the age variable can be written separately.

$$E[P] = AE[\exp(\rho\tau_0\mu/\mu_0)]\sum_{j=1}^{\infty}\prod_{k=1}^{j} E[\exp(-\rho t_k)] \ . \qquad (5)$$

The subscript k in (5) has lost its meaning due to the position of the expectation operator relative to the product sign. Drop the subscript and simplify to get an expression for the closed form:

$$\begin{aligned} E[P] &= AE[\exp(\rho\tau_0\mu/\mu_0)]\sum_{j=1}^{\infty}(E[e^{-\rho t}])^j \\ &= AE[\exp(\rho\tau_0\mu/\mu_0)]E[e^{-\rho t}]/(1 - E[e^{-\rho t}]) \ . \end{aligned} \qquad (6)$$

Occasionally, it might be appropriate to assume that all appliances are new. Consider, for example, the question of choosing between alternative water supplies of different salinity for a new housing subdivision. Also, a housing developer considering alternate locations (where tap water salinity differs) to construct rental apartments would be correct to assume all appliances to be new. In the special case for which the failure time is not a random variable and $t = \mu$ and the initial age is identically zero, that is, all appliances are new, (6) reduces to ?, the usual approximation: $Ae^{-\rho\mu}/(1 - e^{-\rho\mu}) = A/[(1 + r)^{\mu} - 1]$.

Continuing on the assumption that all appliances are new, if the failure time distribution is known, $e^{-\rho t}$ may be integrated against the density function and the exact expected present value may be calculated from (6). Analytical expressions for

[14] We were unable to uncover any references to the problem of estimating the present value of a randomly timed stream of expenditures in the reliability and engineering-economics textbooks that does not take the approximate approach taken the previous salinity-damage studies. We searched the scholarly journals too, but less thoroughly. It seems to be such a fundamental problem that certainly someone has addressed it somewhere, perhaps long ago. We apologize to anyone whose work on this problem we failed to notice.

$E[e^{-\rho t}]$, which is equivalent to the moment generating function, are known for many distributions so, assuming that the initial age of all appliances is zero, (6) can sometimes be evaluated exactly without integration. An approximate expression that only requires estimates of the mean and variance of the failure distribution would be useful when the form of the distribution is not known and there is little confidence in estimates of higher moments. Even given the form of the distribution, if the moment generating function were not known, the use of the approximate expression would be an improvement over the usual approximation, yet would save computation as compared to the exact approach and its repeated numerical integration.

Let us develop the approximate expression. The Taylor series expansion for $e^{-\rho t}$ about the mean μ is

$$e^{-\rho t} = e^{-\rho\mu} - \rho e^{-\rho\mu}(t - \mu) + \frac{\rho^2}{2} e^{-\rho\mu}(t - \mu)^2 + \ldots \quad . \tag{7}$$

We want the expected value of (7):

$$\begin{aligned} E[e^{-\rho t}] &= e^{-\rho\mu} - \rho e^{-\rho\mu} E[(t - \mu)] + \frac{\rho^2}{2} e^{-\rho\mu} E[(t - \mu)^2] + \ldots \\ &\approx e^{-\rho\mu}(1 + \rho^2\sigma^2/2) \quad , \end{aligned} \tag{8}$$

where σ^2, the variance of the distribution of failure times, has been introduced. The approximate formula in (8) may be used to evaluate (6). The error introduced by ignoring the higher order terms in (8) depends on the shape of the density function and the value of the discount rate. The exact approach might prove worthwhile if the discount rate is high and the failure time distribution is highly skewed, multimodal, or otherwise very different from a nice bell-shaped distribution.

The case in which all appliances are new when salinity changes is no doubt exceptional. Ordinarily, the potential beneficiaries of a contemplated reduction in tap water salinity would be living in established communities with a dispersed distribution of appliance ages. It seems reasonable to assume a steady-state distribution of appliance ages in established communities. No other widely applicable possibility presents itself. The result obtained by Booker [1990, p. 105] can be produced from (6) by assuming, as he did, that the initial age distribution is uniform and that the appliances fail as soon as they attain the expected life and no sooner. The uniform probability density function for τ_0 is $1/\mu_0$, which is, of course, implied by the exact width of the distribution given by μ_0. The expected values in (6) may now be evaluated:

$$\begin{aligned} E[\exp(\rho\tau_0\mu/\mu_0)] &= \int_0^{\mu_0} (1/\mu_0)\exp(\rho\tau_0\mu/\mu_0)\,d\tau_0 \\ &= (e^{\rho\mu} - 1)/(\rho\mu) \ . \end{aligned} \tag{9}$$

Therefore, (6) yields $[A/(\rho\mu)](e^{\rho\mu} - 1)e^{-\rho\mu}/(1 - e^{-\rho\mu}) = A/(\rho\mu)$. To convert present value to the equivalent perpetual end-of-year annual payment, multiply by the simple discount rate: the annual cost of appliance replacement is $Ar/(\rho\mu) \approx A/\mu$, which is the result obtained by Booker [1990, p. 105]. The cost per household of appliance replacement is approximately independent of the discount rate. There is a weak dependence due to the use of a simple discount rate consistent with the usual practice in cost-benefit analysis.

The result just obtained is remarkable. It says that a uniform steady-state age distribution that holds for a certain appliance lifetime is immediately transformed to a new steady-state distribution upon a change in salinity that renders a new appliance life. But a strong assumption was made about the life behavior of appliances to arrive at the result: appliance failure is not random in time, but occurs with precise regularity as soon as the appliance reaches a certain age. The uniform age distribution follows as a consequence of the assumed life behavior and the assumption of an initial steady state.

What is the consequence of using more realistic life models and their implied steady-state age distributions? A steady-state age distribution requires a constant number of new appliance units to be put into service per unit time. Let that number be $n(0)$. The probability of survival as a function of age is given by $1 - F(t)$, where $F(t)$ denotes the cumulative probability of failure. Therefore, the number of units surviving at age τ_0 is given by

$$n(\tau_0) = n(0)[1 - F(\tau_0)] \tag{10}$$

The number surviving at any age $n(\tau_0)$ depends on the actual number of appliances in service, M. The probability density function is the fraction of the total at any age, $g(\tau_0) = n(\tau_0)/M$. The number of replacements required per unit time in steady state is $n(0) = M/\mu_0$. Therefore, $n(0)/M = 1/\mu_0$, and the steady-state probability density function of appliance age is

$$g_0(\tau_0) = \frac{1}{\mu_0}[1 - F(\tau_0)] \; . \tag{11}$$

Note that the steady-state age distribution follows from the failure behavior of the appliance.

If the salinity level changes, assuming that the mean failure time changes as a consequence, the age distribution of the existing appliances will be transformed to an effective age distribution under the new salinity level. If the new distribution happens to be the steady-state distribution that is implied by the life behavior of appliances under the new salinity level, then the number of appliance replacements per unit time would immediately attain its new steady-state level. The approximate independence of annual cost on the discount rate found in the case of deterministic failure would be generalized to the case of probabilistic failure.

Let us transform the steady-state probability density function using the effective life model postulated above: $\tau = (\mu/\mu_0)\tau_0$. The inverse transformation gives $\tau_0 = (\mu_0/\mu)\tau$ which we substitute into the probability density function. It is also necessary to multiply by the derivative of the inverse transformation, μ_0/μ. The new density function is

$$g(\tau) = \frac{1}{\mu}[1 - F(\tau\mu_0/\mu)] \ . \tag{12}$$

Comparison of (11) and (12) indicates that if the assumption that the failure distribution function is the same under the new salinity level except for a time-scale factor given by the postulated model is correct, then the transformed density function is also the steady-state density function under the new salinity level. Therefore, the steady-state replacement rate will immediately adjust to the new steady-state level, which is inversely proportional to the new mean failure time.

Consider the case in which all units have identical lifetimes, that is, the case considered by Booker [1990, pp. 102-106]. The cumulative failure distribution function for that case is zero up until the mean failure time, and unity beyond. Equation (11) gives as a special case the uniform age distribution assumed by Booker.

The steady-state number of replacements required per year per appliance is given by the value of the steady-state age density function at age zero: the inverse of the mean failure time. If each appliance has the same price A then a continuous expenditure per appliance at the rate of A/μ is implied, the present value of which is $\int_0^\infty (A/\mu)e^{-\rho t}dt = A/(\rho\mu)$. For any steady-state age distribution, the annual cost per appliance unit, reckoned as an end of year payment, is

$$Ar/(\rho\mu) \approx A/\mu \ . \tag{13}$$

We suggest (13) for reckoning appliance replacement cost except in extraordinary circumstances under which the use of a particular non-steady-state distribution can be justified.

WHAT ABOUT APPLIANCES STILL IN SERVICE?

A controlled experiment for measuring the failure time of appliances may be terminated well before all of the appliances have failed; new ones may be added after the test begins; and some of them may be removed from testing for reasons unrelated to failure. Because the failures of the appliances failing soonest are more likely to be observed, the statistical descriptions of the life data, such as the mean failure time, are biased if the non-failed appliances are ignored. By surveying plumbers or other appliance service personnel, one cannot discover much of anything about appliances that have not been replaced: one is limited to the information about already failed appliances. In a household survey, one may ask, of course, how long the previous appliance lasted, but there is another relevant piece of information: the age of the current appliance. A household survey is akin to a controlled experiment in which the entry of every appliance into the experiment occurs at a random time and is replaced by another appliance upon failure. However, there is a difference that we illustrate with a thought experiment.

Suppose that the distribution of failure times for water heaters has this peculiar property: there is a 50 percent chance that a water heater will last exactly ten years and a 50 percent chance that it will last exactly 50 years. The expected life is then $.5(10) + .5(50) = 30$ years. If the same failure distribution has been in operation for a long time and if the total number of water heaters in service is constant, then the number of each type replaced is equal to the number of each type failing in a given year. In other words, there is an equilibrium population of each type of heater that would emerge after a long period without population or technological change. In equilibrium, the expected number of failures per year of the long-lasting heaters is $N/50$ where N is the equilibrium population of long-lasting heaters. The expected number of failures per year of the early-failing heaters is $M/10$, where M is equilibrium population of early-failing heaters. The number of replacements of each type is $.5(N/50 + M/10)$ which must, in equilibrium, equal the number of failures of each type. Therefore, $N/50 = M/10$; there are five times more long-lasting heaters in service at any moment. An appliance repairer or plumber, observing equal numbers of failures of each type, would correctly conclude from the records that the mean failure time is $.5(10) + .5(50) = 30$. A surveyor of households who found that every respondent gave the age at failure of the previous water heater, and who ignored in-service water heaters, would likewise correctly estimate the mean failure time, for, by assumption, there would be an equal chance of a previous water heater having been of either type.

There are problems with this scenario. First, even without population or technological change, it is likely that a surveyor of households would find some people on their first water heater, perhaps because they have just set up house recently (within the last 50 years). A bias appears toward lower lifetimes because the water heaters ignored (the ones recently installed) are more likely to be of the long-lived type. Second, there is likely to have been population change or technological change which would upset the postulated equilibrium. With technological change, plumbers, appliance repairers, and surveyors of households who ignored in-service water heaters would not have access to important newly emerging information on the lives of newly developed water heaters. With population increase, records would seem to indicate a reduction in water heater lifetime as the repairers and plumbers began to see with greater frequency the failures of early-failing water heaters.

Previous salinity damage studies have not taken in-service appliances into account. Although Coe includes a question on age of current water heater in his survey of households, he does not discuss how or whether he uses the information [Coe 1982]. Other household surveys do not ask questions relating to appliances currently in service (for example, Metcalf & Eddy [1972]). Studies relying only on appliance service providers, plumbers, or others whose knowledge of appliance failure is derived from observed failures only, necessarily ignore in-service water heaters (for example, Black & Veatch [1967]; d'Arge and Eubanks [1978]).

In a world of unpredictable technological and population change, no method could acquire completely unbiased information on the life expectancy of appliances and relate this to the benefits of improvements in water quality. However, by including data on in-service appliances, one could hope to make a nearer approximation to the truth.

The method of accelerated testing

The cost of laboratory measurements of the lifetimes of durable goods can be high if a test must continue until some fairly large fraction of the appliances on test have failed. A life test could be conducted more quickly and cheaply if time could somehow be "accelerated." Frequently, some environmental variable such as temperature, vibration, or humidity causes more rapid deterioration and failure. It is sometimes accurate and useful to view such an accelerated deterioration as an acceleration of time [Mann and others, 1974; Kalbfleisch and Prentice, 1980]. The method of accelerated testing depends on the assumption that an environmental stress does not affect anything about the failure except the speed at which it occurs. By testing articles under extremes of environmental stress, an experimenter can achieve a high proportion of failures quickly. If the acceleration law and the form of the failure time distribution function are known from theory or can be determined empirically, the properties of the distribution of failure times at normal operating conditions can be determined from an accelerated test.

We can treat data on the lifetimes of appliances and fixtures at various salinity levels as if the data have come from an accelerated reliability test. However, we are not interested chiefly in the failure behavior at low or zero salinity. Rather, we want to know the acceleration law (which relates failure probability to salinity) so that we can use it to measure the cost imposed by salinity in the form of decreased service lives of appliances.

A generalized model for accelerated testing

Let the failure time under normal or baseline operating conditions Z be a random variable from the probability density function $f(z)$. The reliability function $R(z) \equiv 1 - F(z)$, where $F(z)$ is the cumulative distribution function of Z. $R(z)$ gives the probability of survival at time z. Suppose that a given number of appliances are put on test and the test is ended with some appliances still running. The failure times of the appliances still in operable condition are, of course, not observed. The amount of time they have been in operation at the end of the test is a *right censored* observation of the failure time. Now suppose that T is accelerated time: real time in an accelerated test. The baseline time Z (which is not observed directly in an accelerated test) is related to the observed accelerated time T by the acceleration transformation $z = g(s;\beta)t$ where s is a vector of environmental variables and β is the vector of parameters by which the environmental variables influence the failure time. The environmental variables are defined as deviations from nominal conditions so that they vanish at nominal or baseline conditions and are non-negative under test conditions. Under the influence of the time-accelerating conditions, less time T must pass for the same deterioration effect under nominal conditions represented by time Z. This implies that $g(s;\beta) \geq 1$. For example, using $z = (1/e^{\beta_1 s_1})t$, given that s_0 is non-negative, one would expect the parameter β_1 to be negative. The objective of an accelerated test is to estimate the parameters of the baseline density function $f(z)$, which holds under normal operating conditions. The functional forms of the reliability function and the acceleration transformation function must be known for this purpose. The acceleration transformation function and its parameters are simultaneously estimated along with the parameters of the reliability function $R(z)$, called the baseline reliability function.

The following acceleration function, which is a generalization of the usual pure-exponential acceleration function, describes the behavior of the water heater data from our survey of households better than the pure-exponential acceleration function is able to do.

$$g(s;\beta) = 1/\{[\beta_0 + (1 - \beta_0)e^{\beta_1 s_1}]e^{\beta_2 s_2}\}\ , \tag{14}$$

where s_1 is salinity and s_2 is some other environmental variable such as, in this case, the number of people living in the household. The model is a generalization of the usual accelerated-testing model because, if $\beta_0 \equiv 0$, (14) reduces to the special case of the usual pure-exponential model for accelerated testing.

After the baseline reliability function and the acceleration function have been determined, the reliability function at any values of environmental variables can be calculated. From the reliability function and the initial age distribution function, one can evaluate the exact cost function (6). Or, if all appliances are assumed to be new when salinity changes, one may calculate the mean and variance of the reliability function as a function of the environmental variables and use these with the approximate expression (8) to approximate the cost function (6). In the more common case in which a steady-state age distribution seems appropriate, (13) is to be preferred.

The generalized model gives the expected service life of the appliance as a function of environmental variables and the estimated parameters:

$$\begin{aligned}\mu &= Y(\mu_0,\beta_0,\beta_1,\beta_2,s_1,s_2) \\ &= \mu_0/\{[\beta_0 + (1-\beta_0)e^{\beta_1 s_1}]e^{\beta_2 s_2}\}\ ,\end{aligned} \tag{15}$$

where μ_0 is the mean service life under baseline conditions, that is, when $s_1 = s_2 = 0$. The standard deviation of the service life follows the same acceleration law as the mean:

$$\begin{aligned}\sigma &= Z(\sigma_0,\beta_0,\beta_1,\beta_2,s_1,s_2) \\ &= \sigma_0/\{[\beta_0 + (1-\beta_0)e^{\beta_1 s_1}]e^{\beta_2 s_2}\}\ .\end{aligned} \tag{16}$$

Denoting the same function for the mean and standard deviation by different letters will provide for simpler notation below.

One may use the method of maximum likelihood to estimate the parameters [Nelson, 1982, p. 313]. A desirable property of maximum-likelihood estimators is that,

> under certain conditions (usually met in practice) on the distribution and data and for 'large' sample sizes, the cumulative distribution function of a [maximum-likelihood] estimator is close to a normal one whose mean equals the quantity being estimated and whose variance is no greater than that of any other estimator [Nelson, 1982, p. 313].

The log-likelihood function for data y_i with multiple right censoring drawn from a two-parameter distribution is [Nelson, 1982, p. 376]:

$$\mathcal{L} = \sum_i{}' \log[f(y_i;\lambda,\delta)] + \sum_i{}'' \log[R(y_i;\lambda,\delta)]\ , \tag{17}$$

where the first sum is over the uncensored observations (observed failures) and the second sum is over the censored observations (in-service appliances). We transformed the survival data in the present work by the natural log and the time-acceleration transformation and used an extreme value distribution for fitting. Thus, we assumed $Y = \log\{[\beta_0 + (1-\beta_0)e^{\beta_1 s_1}]e^{\beta_2 s_2} T\}$, where T represents the age at failure or the current age of a non-failed appliance, to be distributed according to the extreme value reliability function

$$R(y) = \exp[-\exp(\frac{y-\lambda}{\delta})]\ . \tag{18}$$

The log transformation implies a Weibull distribution in the raw data [Nelson, 1982, p. 43]. The reliability function $R(y)$ and the corresponding probability density distribution given by $f(y) = -dR/dy$ was inserted into (16), the log-likelihood function. Then the log-likelihood function was maximized with respect to λ, δ, β_0, β_1, and β_2. Estimates of the mean and standard deviation of the baseline distribution are given by $\mu_0 = e^{\lambda}\Gamma(1 + \delta)$ and $\sigma_0 = e^{2\lambda}\{\Gamma(1 + 2\delta) - [\Gamma(1 + \delta)]^2\}$, where $\Gamma(\circ)$ denotes the gamma function.

Propagation-of-error formulas

We derived estimates of the covariance matrices for the parameters using large-sample approximations that are strictly valid only for linear estimation [Nelson, 1982, pp. 394-395]. We obtained standard errors for the mean and standard deviation of the baseline distribution and the correlation between by propagation of error [Nelson, 1982, p. 374]. The propagation of error formulas used here are approximations that ignore the terms involving moments of the probability distributions of the parameters of third and higher order [Hahn and Shapiro, 1967, pp. 255-257].

Let us denote the squared standard error of a quantity x by $S^2(x)$ and the partial derivatives of Y and Z with respect to the parameters (evaluated at estimated parameter values with implied dependence on environmental variables) by a numerical subscript. For precisely specified values of the environmental variables, the squared standard error of the mean service life is given by

$$\begin{aligned} S^2(\mu) = {} & Y_1^2 S^2(\mu_0) + Y_2^2 S^2(\beta_0) + Y_3^2 S^2(\beta_1) + Y_4^2 S^2(\beta_2) \\ & + 2[Y_1 Y_2 Cov(\mu_0,\beta_0) + Y_2 Y_3 Cov(\beta_0,\beta_1) + Y_3 Y_4 Cov(\beta_1,\beta_2) \\ & + Y_1 Y_4 Cov(\mu_0,\beta_2) + Y_1 Y_3 Cov(\mu_0,\beta_1) + Y_2 Y_4 Cov(\beta_0,\beta_2)] \, . \end{aligned} \tag{19}$$

The squared standard error of the standard deviation of the service life is given by

$$\begin{aligned} S^2(\sigma) = {} & Z_1^2 S^2(\sigma_0) + Z_2^2 S^2(\beta_0) + Z_3^2 S^2(\beta_1) + Z_4^2 S^2(\beta_2) \\ & + 2[Z_1 Z_2 Cov(\sigma_0,\beta_0) + Z_2 Z_3 Cov(\beta_0,\beta_1) + Z_3 Z_4 Cov(\beta_1,\beta_2) \\ & + Z_1 Z_4 Cov(\sigma_0,\beta_2) + Z_1 Z_3 Cov(\sigma_0,\beta_1) + Z_2 Z_4 Cov(\beta_0,\beta_2)] \, . \end{aligned} \tag{20}$$

With (19) and (20), one may calculate the estimated standard errors for the mean and standard deviations calculated by (15) and (16) for given values of the environmental variables. The covariance between the mean and standard deviation, which is required for propagation of error to a function of both the mean and standard deviation, is given by

$$
\begin{aligned}
Cov(\mu,\sigma) = {} & Y_1Z_1Cov(\mu_0,\sigma_0) + Y_1Z_2Cov(\mu_0,\beta_0) \\
& + Y_1Z_3Cov(\mu_0,\beta_1) + Y_1Z_4Cov(\mu_0,\beta_2) \\
& + Y_2Z_1Cov(\beta_0,\sigma_0) + Y_2Z_2Cov(\beta_0,\beta_0) \\
& + Y_2Z_3Cov(\beta_0,\beta_1) + Y_2Z_4Cov(\beta_0,\beta_2) \\
& + Y_3Z_1Cov(\beta_1,\sigma_0) + Y_3Z_2Cov(\beta_1,\beta_0) \\
& + Y_3Z_3Cov(\beta_1,\beta_1) + Y_3Z_4Cov(\beta_1,\beta_2) \\
& + Y_4Z_1Cov(\beta_2,\sigma_0) + Y_4Z_2Cov(\beta_2,\beta_0) \\
& + Y_4Z_3Cov(\beta_2,\beta_1) + Y_4Z_4Cov(\beta_2,\beta_2) \ .
\end{aligned}
\qquad (21)
$$

Equation (21) is necessary for the calculation of the standard error of the cost of appliance replacement if the method of reckoning replacement cost for the "all new" age distribution using the approximation (8) developed above is used.

APPLICATION OF THE SUGGESTED TECHNIQUES TO THE SURVEY DATA

The survey described in Chapters 4 and 5 provided the data for application of the accelerated-testing method to salinity impacts on the life of household appliances. First, visual evidence (see Figure 4) that the usual accelerated-testing method, with the pure exponential function, does not describe the water heater data well, provided motivation to generalize the accelerated-testing method. The water heater data is represented in Figure 4 with product-limit estimates at each salinity level. The product-limit method (also called the Kaplan-Meier method) is a nonparametric method that may be used to estimate the reliability function when not all units have failed [Kaplan and Meier 1958][15]. The product-limit estimates of mean life in Figure 4 are

[15] In the limiting case of uncensored data, the product-limit estimate of the reliability function is the so-called empirical reliability function. For example, suppose that from a survey of three households, failures are observed at 7, 9, and 10 years. The empirical reliability function (giving probability of survival) would be unity up to 7 years, 2/3 between 7 and 9 years (two out of three units surviving), (2/3)(1/2) = 1/3 between 9 and 10 years (half of those having survived up until 7 years surviving beyond 9 years), and (2/3)(1/2)(0/1) = 0 above 10 years. Now introduce the complication of censored data: an 8 year old in-service unit. Now, there had been 4 units under observation, so the failure at 7 years brings the reliability function to 3/4. The censored observation at 8 years is not a failure, but it removes one unit from the pool at 8 years. The distribution function is still estimated at 3/4 up to 9 years, but the failure at 9 years is based on a pool of only two units, so between 9 and 10 years, the estimated distribution function is (3/4)(1/2) = 3/8. Above 10 years, the estimated distribution function is (3/4)(1/2)(0/1) = 0. From the reliability function estimated by

accompanied by error bars indicating the standard error of the mean life estimates. The smooth curve showing the accelerated-testing estimates produced using a pure exponential acceleration function does not capture the apparent initial steep drop in lifetime with salinity and the subsequent reduction in the rate of decline (Figure 4).

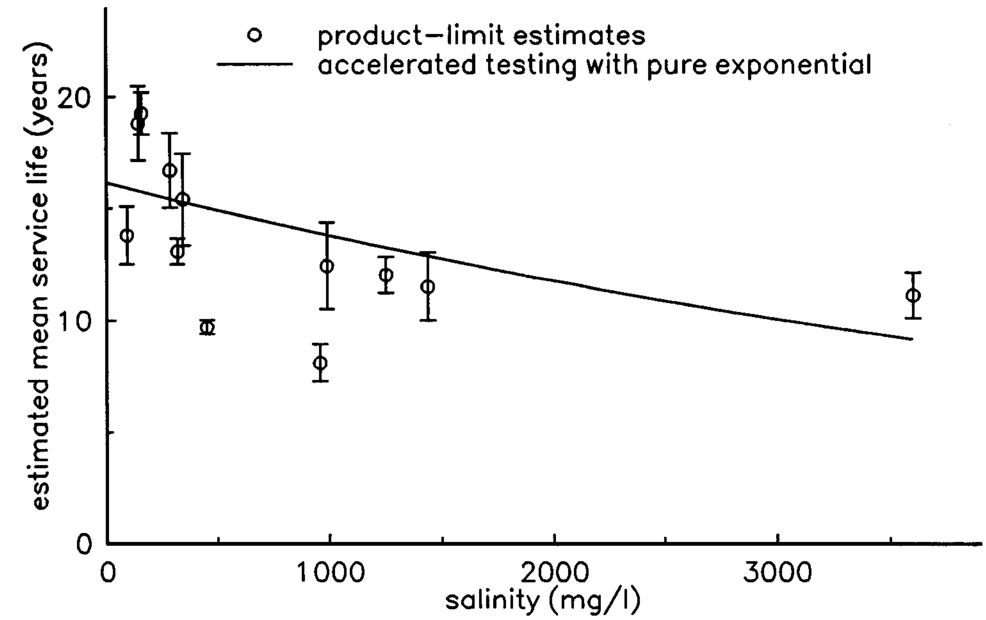

Figure 4. Water heater mean life as a function of salinity estimated by a pure-exponential accelerated-testing model and the product-limit method, for which ± one standard error is also shown.

The generalized accelerated-testing model (14) was fitted by the method of maximum likelihood to the water heater data from our residential survey under the assumption of a Weibull distribution and $\beta_2 \equiv 0$ (effect of s_2 not allowed). The product-limit estimates are in close agreement with the generalized accelerated-testing estimates; the arithmetic means of observed failures lie below the other estimates (Figure 5).

For the water heater data, ignoring the censored observations results in an underestimate of the true mean lifetimes if the product-limit estimates or the accelerated-testing estimates are taken to be much more accurate (Figure 5). The accelerated-testing method allows the information contained in the censored observations to be used. The accelerated-testing method has the advantage over the

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the product-limit method, one may estimate the mean of the distribution (and higher moments).

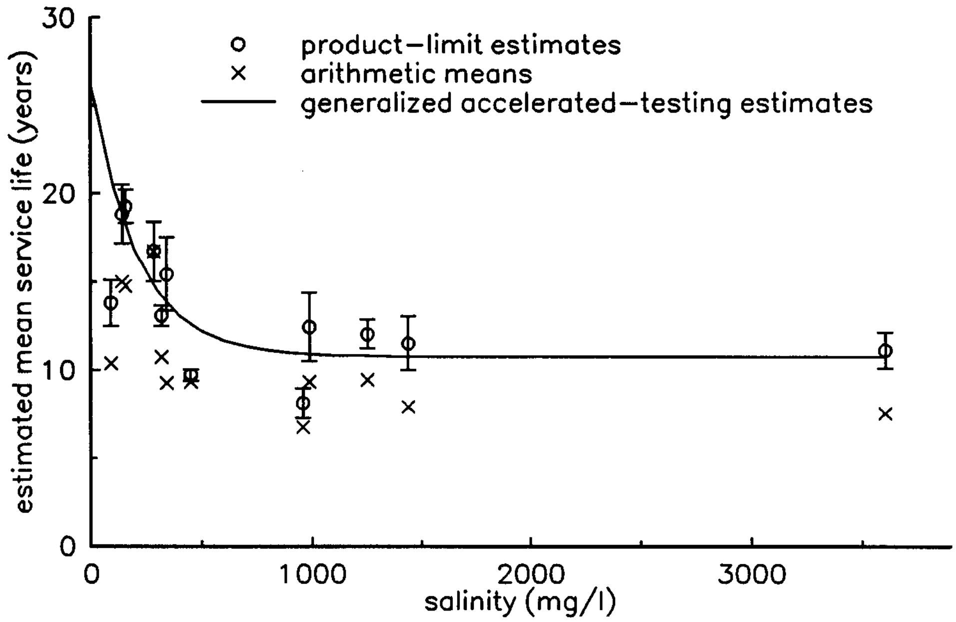

Figure 5. The generalized accelerated-testing method applied to water heater data.

product-limit method (which can also use censored data) that it lumps all of the data together to produce a single semi-empirical function that applies at any specified level of the environmental variables. The accelerated-testing method also avoids the tendency of the product-limit method to ignore censored data at the upper tail of the distribution and to produce for that reason biased estimates.

Because ignoring censored observations in the household data resulted in underestimating the mean service life of water heaters, we should also expect plumbers and appliance repair firms to have underestimated the mean life of water heaters. It appears that they did, if the estimates produced using the generalized accelerated-testing method with household data are taken as a benchmark (Figure 6).

Up to now we have presented no evidence that the Weibull distribution function adequately models the failure time distribution. To evaluate the Weibull form, we estimated the baseline ($s_1 = s_2 = 0$) Weibull reliability function for the water heater using the model (14) with s_2 representing the number of people in the household (Figure 7). We computed, for comparison, the nonparametric reliability function estimated by the product-limit method applied to data which had been transformed (to $s_1 = s_2 = 0$) by the time-acceleration function determined by the generalized accelerated-testing method (Figure 7).

Has a transformation that allows the model to fit the data been found? The visual evidence indicates that it has. The comparison is somewhat circular because the raw data input to the product-limit calculations has been transformed to baseline

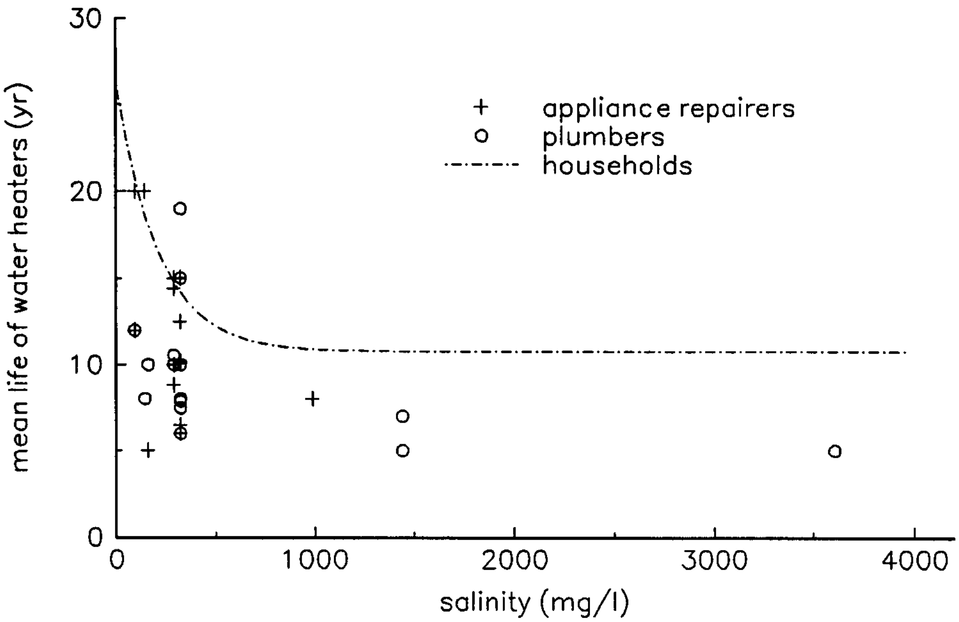

Figure 6. Comparison of mean life of water heaters estimated by plumbers and appliance repairers with household estimates using the generalized accelerated-testing method.

conditions as determined by fitting the generalized accelerated-testing model. The approximately linear shape of the plot of the log of the negative log of the product-limit distribution functions versus the log of the failure times had also suggested the Weibull distribution [Kalbfleisch and Prentice, 1980, p. 24]. Using the SAS[16] procedure LIFEREG (which can not handle the exponential-plus-constant acceleration function), we tried several other distributions (exponential, two-parameter gamma, log-normal, logistic, and log-logistic) with the data pertaining to water heaters and the other appliances. The Weibull distribution produced log-likelihood estimates comparable to

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[16] SAS (not an acronym) is a registered trademark of SAS Institute Inc., Cary, NC, USA [SAS 1990; Aronson and Aronson, 1990]. LIFEREG is a SAS procedure for life regression, that is, accelerated-test modelling.

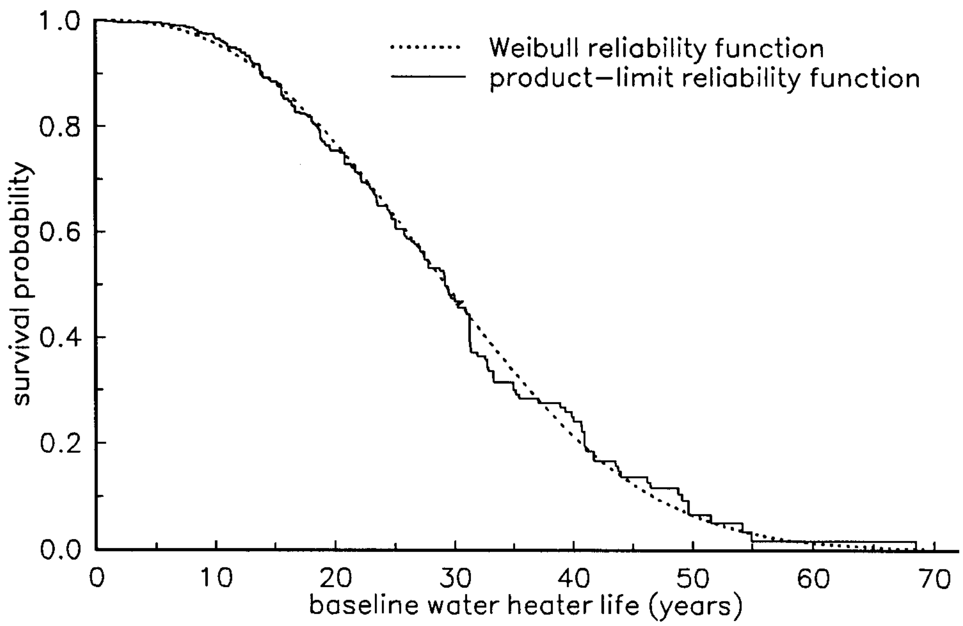

Figure 7. Estimated baseline Weibull reliability function and product-limit reliability function for data transformed to the baseline by the time-acceleration function.

those produced by the gamma and log-logistic distributions.[17]

The suggested improvements in statistical method applicable to the case in which all appliances are assumed to be new affect the estimates of annual marginal cost of appliance replacement[18] per appliance, especially at lower salinity levels, for the water heater data (Figure 8). We have avoided the dependence of the marginal cost of water heater replacement on the price of water heaters in Figure 8 by comparing the marginal cost coefficient, which, if multiplied by the price of water heaters, would give the annual marginal cost per appliance of salinity attributable to water heater replacement. We used the approximate expression (8) and a model

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[17] For a simple water heater model, the log-likelihood was -315.3 for the gamma distribution, -316.7 for Weibull, -317.6 for log-logistic, -333 for log-normal, -437 for exponential. For one of the clothes washer models log-likelihood was -280 for Weibull and -283 for log-logistic. The larger (less negative) the log-likelihood the better the fit. In that sense, the Weibull distribution outperformed every other distribution except the gamma, which is more complicated.

[18] By "marginal cost of appliance replacement" we mean the derivative with respect to salinity of the cost of appliance replacement.

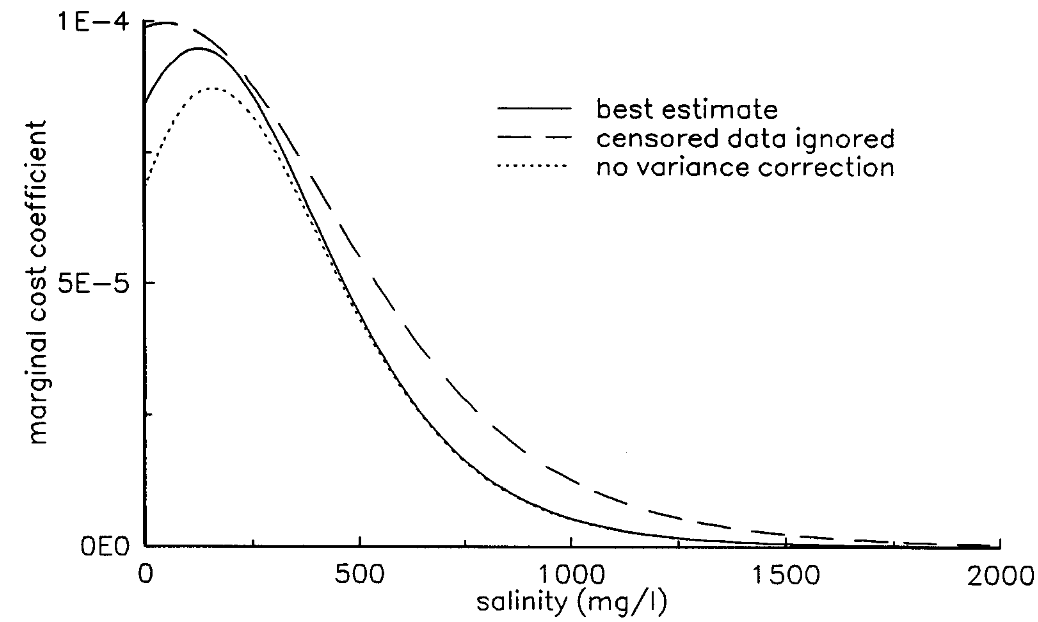

Figure 8. Effect of ignoring censored data and random timing of replacement expenditures on the estimated annual marginal cost per appliance of water heater replacement using data from the present study.

estimated by the generalized accelerated-testing method to produce the "best estimate" in Figure 8. The use of (8) implies, of course, that the appliances are all new when salinity changes. Ignoring the censored data exaggerated the damage; failing to account for random timing of replacement expenditures resulted in an underestimate of damage (Figure 8).

The model we have estimated of the effect of salinity on water heater life (combined with the suggested method of accounting for the random timing of replacement expenditures applicable to the case in which all appliances are new) implies an annual cost of water heater replacement per appliance as a function of salinity that differs greatly from estimates derived from the models estimated by Tihansky [1974] and d'Arge and Eubanks [1978], which are based on other data (Figure 9). The studies cited for comparison, like the estimates provided, are based on an "all new" initial age distribution. The benefit of a reduction in salinity from, say, 1000 mg/l to 500 mg/l, represented in Figure 9 by the area under the curves between those salinity levels, is several times smaller for the estimates developed here. On the other hand, the model estimated here implies a greater cost of salinity than does Tihansky's model at low salinity levels.

Some of the differences between present estimates of salinity damage to appliances and estimates from previous studies are attributable to the methodological

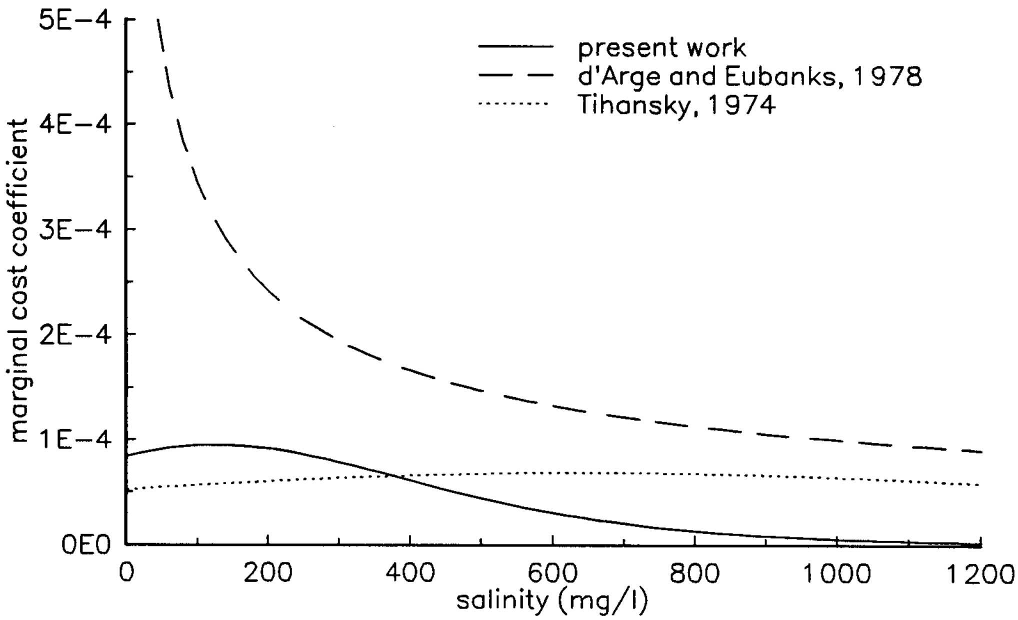

Figure 9. Comparison of annual marginal cost per appliance of water heater replacement at ten percent discount rate using estimates of service life from the present and previous studies.

improvements suggested here. The comparisons in Figure 8 suggest that the differences in cost implied by different models are too great to be accounted for solely by the methodological differences we have explored. Also, as Booker [1990, pp. 102-106] made apparent and as we will see in Chapter 6, assuming a steady-state age distribution has little effect on estimates of appliance replacement cost.

A corollary of the suggestion that better estimates of mean life are obtained if in-service appliances are taken into account is that household surveys are potentially more accurate than surveys of plumbers and appliance repair firms. But there is another reason why household surveys might produce more accurate results: the questions on a household survey relate to definite events happening at a particular time. Memory is certainly fallible, but, for major appliances, expenditures are large compared to many other household expenditures and purchases of major appliances may be associated with other significant events, such as moving, getting married, having a child, or getting a job. Appliance repair shops or plumbers asked to estimate the average life of water heaters are not remembering a specific event, but a host of events in which they had little personal interest.

The work of Jaeger and Pennock [1961] lends support to the claim that household surveys can produce accurate data on appliance lifetimes. They investigated the consistency over time of household responses to questions relating to electric washing machines. Identical households were asked (in person, in two otherwise different surveys administered approximately one year apart) identical questions dealing with the type[19] of washing machine owned, year of purchase, and whether the machine was bought new or used. Consistency over time of the responses of a single household does not prove accuracy, but lack of consistency does prove a lack of accuracy in at least one of the responses. The sample size was large, with 2,023 responses to the age question. A third of respondents, 33.4 percent, gave exactly the same date of purchase. Almost another third, 30.5 percent, gave answers differing by one year, with 55 percent of the second responses indicating earlier purchase and 45 percent indicating later purchase. Another 12.4 percent gave responses differing by two years with half of the second responses indicating earlier purchase and half indicating later purchase. Therefore, 76 percent of responses differed by two years or less. Roughly equal percentages reported earlier dates of purchase in the second survey as reported later dates of purchase.

Tihansky's model is based on data from, in part, the household survey by Metcalf & Eddy [1972]. The model by d'Arge and Eubanks is based on data from surveys of plumbing contractors and appliance dealers. The fact that Tihansky's model produces results closer to ours than does the model estimated by d'Arge and Eubanks is consistent with the possibility that household surveys are better than surveys of appliance repair firms and households even if in-service appliances are not taken into account.

Other factors that could be responsible for the differences in estimated cost between the various studies are technological change and differences in the proportional mixtures of ions in the waters of the areas studied. The only reliable way to adjust salinity damage estimates to technological change is to perform new studies, of which the present work is an example. One way to take account of effect of the proportional mixture of ions would be to include areas with very different mixtures and generalize the statistical models accordingly. However, because frequent updates seem to be required anyway, it might be worthwhile to perform a separate salinity damage study for any large project that would reduce salinity without appreciably affecting the proportional mixture of ions. To evaluate the benefits of the salinity reduction project, it would not be necessary to know the effect of each ion.

[19] The categories have been washed away, so to speak, in the tide of technological change: manually operated, semi-automatic, and fully automatic.

CHAPTER 6

EMPIRICAL LIFE MODELS OF WATER-USING APPLIANCES

This chapter presents life models estimated using the generalized accelerated-testing method developed in Chapter 5 for all of the household appliances for which we collected data in our survey of households in the Arkansas Valley of Colorado. The life models presented here form the basis of the cost functions to be described in Chapter 7. The models could be used with different assumptions (for example: discount rates, fractions of households using the appliances, or prices of appliances) to construct cost functions for different situations.

DEFINITIONS OF VARIABLES

The variable representing the number of people living in the household, "PEOPLE," takes on the values 1 through 6 corresponding respectively to 1 through 5 and 6 or more people living in the household. The variable representing the number of clothes washer loads per week reported "done in the home" takes on the values 1 through 5 corresponding respectively to 0, 1-2, 3-5, 6-8, and 9 or more loads done in the home.[20] This variable carries the label "LOADS." The salinity corresponding to the household is denoted by "SALINITY." (See Chapter 3 for information on measurements of the salinity of the surveyed areas.) The parameters of the extreme value distribution are denoted by "LAMBDA" and "DELTA." Other parameters used in the last chapter are denoted by the obvious names MUO, SIGMAO, BETAO, BETA1, and BETA2.

STATISTICAL ANALYSIS

The generalized accelerated-testing method was used to fit parametric distributions to the failure data as described in the last chapter. The SAS procedure NLIN was used for estimating the models except when, as noted, the SAS[21] procedure LIFEREG was applied. (See Ragan, 1992, Appendix 2 for the program using the NLIN procedure.) The LIFEREG procedure cannot be used for estimating an exponential-plus-constant model. The program Ragan wrote within the procedure NLIN

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[20] A better choice for representing the categories would have been 0, the midpoints of the ranges, and 9. Anyone wanting to use the clothes washer model that uses LOADS could use the same categorizations of the number of loads per week or, with other categorizations, could devise a transformation. However, as we see it, the models containing LOADS and PEOPLE are mostly useful for assessing the simpler models with only salinity as an environmental variable.

[21] See footnote 16. NLIN is a SAS procedure for nonlinear least-squares fitting.

maximizes the log-likelihood function for the model as presented in Chapter 5. His program using NLIN can estimate a pure-exponential model or an exponential-plus-constant model. The two methods (using LIFEREG and NLIN) gave virtually the same results on cases which they both could handle. After establishing confidence in the program (by comparison with LIFEREG), he did not continue to estimate cases which had already been estimated using using LIFEREG. When needed, approximate large-sample 90 percent and 95 percent confidence intervals for the parameters of each model were constructed using the normal distribution by multiplying the standard errors by 1.645 and 1.960 respectively.

Water heaters

There were 747 observations of water heater service lives, including both censored and uncensored observations. Of these, 216 were uncensored and 531 were censored.

Consider whether to include the constant term, BETA0, in the water heater model. A comparison of the coefficient associated with salinity in cases 1 and 2 in Table 9 indicates the importance of this decision: without the constant term, the estimated effect of salinity on water heater life is much lower at low levels of salinity. One can conclude from the increase in the log-likelihood that the inclusion of the constant term produces a better fit. Now consider a significance test: is the constant term significantly different from zero? An approximate 95 percent confidence interval for the constant term in case 2 is (0.289, 0.535). As the range does not include zero, we can reject, at the .05 significance level, the hypothesis that the constant term is equal to zero.

Table 9 Estimated parameter values and standard errors for water heater models.

Case	Parameters associated with SALINITY $(BETA0/10^{-3})$[a]	SALINITY $(BETA1/10^{-3})$	PEOPLE $(BETA2/10^{-3})$	log-likelihood
1	-	-0.158 ± 0.020	-	-319
2	412 ± 63	-4.72 ± 1.38	-	-307
3	412 ± 63	-4.71 ± 1.35	-61.8 ± 23.5	-301

[a] Values have been divided by 10^{-3}.

The decision whether to include the variable representing the number of people living in the household is less important from the standpoint of salinity damage. The coefficients relating to salinity hardly changed when PEOPLE was included. The models represented by cases 2 and 3 serve equally well as models of the effect of salinity on water heater service life. The parameter associated with PEOPLE is significant at the .05 level [95 percent confidence interval: (−0.108, −0.016)]. The model represented by case 3 can be used when a more complete description is desired.

Clothes washers

There were 689 observations of clothes washers. Of these, 161 were uncensored and 528 were censored.

It is apparent from the large standard errors associated with the constant term BETA0 (in cases 2, 4, and 6, Table 10) that the exponential-plus-constant model is not superior to the pure-exponential model as a description of the data. The parameters LOADS and PEOPLE in cases 3 and 5 respectively have estimated respective 95 percent confidence intervals of (−0.201E−3, −0.075E-3) and (−0.196E−3, −0.074E−3). Therefore, they are both significant at the .05 level. Case 3 produces the best fit as judged by the log-likelihood. However, the parameter associated with salinity BETA1 in case 3 is almost equal to the same parameter in case 1, where salinity is the only explanatory variable.

Table 10 Estimated parameter values and standard errors for clothes washer models.

Case	Parameters associated with				log-likelihood
	SALINITY		PEOPLE	LOADS	
	BETA0/10^{-3}	BETA1/10^{-3}	BETA2/10^{-3}	BETA2/10^{-3}	
1	-	-0.142±0.028	-	-	-293
2	460±313	-0.372±0.444	-	-	-293
3	-	-0.138±0.030	-	-172±32	-270
4	428±985	-0.228±0.656	-	-173±32	-271
5[a]	-	-0.135±0.031	-128±26	-	-280
6	316±958	-4.71±1.35	-127±30	-	-279

[a] SAS procedure LIFEREG used.

Dishwashers

There were 399 observations of dishwasher service lives: 316 censored and 83 uncensored.

The dishwasher models that included the parameter BETA0 would not converge, probably because of overparameterization.[22] When we used the pure exponential model, with or without the inclusion of PEOPLE, we found BETA1 to be not significant at the .1 level (Table 11). In other words, no significant effect of salinity on the service lives of dishwashers was found.

Table 11 Estimated parameter values and standard errors for dishwasher models.

Case	Parameter associated with SALINITY ($BETA1/10^{-3}$)	Parameter associated with PEOPLE ($BETA2/10^{-3}$)	log-likelihood
1	-0.0782±0.061	-	-158
2	-0.0954±0.061	-96.27±38.18	-154

Water softeners

There were 126 observations of water softener service lives: 21 uncensored and 105 censored.

In cases 1 and 2 the parameter associated with salinity is significantly different from zero at the .05 level (Table 12). The parameter BETA1 in case 3 is not significantly different from zero even at the .1 level; we abandon the model for case 3. The parameter associated with the number of people in the household is significantly different from zero at the .05 level in case 2. In view of the precision of the estimates, BETA1 is approximately the same in cases 1 and 2.

Reverse-osmosis units and distillation units

Twenty-five respondents reported having reverse-osmosis units. Only one failure time and only nine censored observations of service life were reported. Six respondents reported having distillation units. We could not extract any useful information relating salinity to service life from these data.

[22] With little or no variation in lifetime with salinity to be accounted for, both BETA1 (tending toward zero) and BETA2 were trying to account for the constant lifetime.

Table 12 Estimated parameter values and standard errors for water softener models.

Case	Parameters associated with SALINITY		PEOPLE	log-likelihood
	BETA0/10^{-3}	BETA1/10^{-3}	BETA2/10^{-3}	
1	-	-0.190 ± 0.085	-	-50.2
2	-	-0.176 ± 0.079	226 ± 73	-46.5
3	288 ± 150	-2.04 ± 1.53	-180 ± 73	-45.4

Humidifiers

There were 89 observations of humidifier service life: nine uncensored and 80 censored. The parameters associated with SALINITY and PEOPLE are not significantly different from zero even at the .1 level (Table 13). In other words, we found no significant effect of salinity on the service lives of humidifiers.

Table 13 Estimated parameter values and standard errors for humidifier models.

Case	Parameter associated with SALINITY (BETA1/10^{-3})	PEOPLE (BETA2/10^{-3})	log-likelihood
1	-0.242 ± 0.173	-	-29.9
2	-0.272 ± 0.168	-236 ± 218	-28.9

The results for humidifiers make sense if the tendency of users to equalize salinity is considered. The addition of table salt to the water is advised for the proper functioning of inexpensive steam humidifiers if tap water salinity is low. Too high a salinity also prevents proper functioning. Residents of the lower valley may find it necessary to dilute the tap water with bottled water, home reverse-osmosis treated water, or some other low salinity water. Or, if accumulation of scale is a problem, they might use bottled water with added table salt. The more expensive "cool" humidifiers are intended for use with bottled or reverse-osmosis treated water even in areas of low tap water salinity.

Garbage disposers

There were 429 observations of garbage disposers: 90 reported failures and 339 units in service. Table 14 gives estimates of the parameters of the acceleration functions of the estimated models for garbage disposers. The parameter associated with salinity, BETA1, in case 1 is almost but not quite significantly different from zero at the .05 level; it is significantly different at the .1 level. BETA1 becomes significant at the .05 level when, in case 2, PEOPLE is included. The inclusion of the constant term BETA0 in case 3 hides the significant relationship between salinity and service life found in cases 1 and 2. The relationship revealed by cases 1 and 2 between salinity and service life seems rather weak: a reduction in mean service life of only about 30 percent is predicted by the model in case 1 in response to an increase in salinity from zero to 4000 mg/l: $\exp[4000(-85\times10^{-6})] = 71\%$. Partly as a result of the weak relationship, the model in case 3 seems overparameterized, with both the constant term and the exponent term trying to explain an almost constant lifetime as a function of salinity.

Table 14 Estimated parameter values and standard errors for garbage disposer models.

Case	Parameters associated with SALINITY: $BETA0/10^{-3}$	SALINITY: $BETA1/10^{-3}$	PEOPLE: $BETA2/10^{-3}$	log-likelihood
1	-	-0.0846 ± 0.0412	-	-190
2	-	-0.0925 ± 0.0421	-123 ± 41	-185
3	672 ± 225	-0.59 ± 1.25	-119 ± 44	-185

Evaporative coolers

There were 347 observations of evaporative coolers: 49 observed failures and 298 units in service. Table 15 gives estimates of the parameters of the acceleration functions of the estimated models for evaporative coolers. BETA1 in the model estimated in case 1 is significantly different from zero at the .05 level. There is no point in including PEOPLE (case 2) since its parameter is insignificant. We take the fact that the exponential-plus-constant form (case 3) hides the significant relationship found in cases 1 and 2 between salinity and service life as an indication that the model for case 3 is overparameterized. Therefore, the model in case 1 is the only acceptable model of the effect of salinity on service life of evaporative coolers.

Table 15 Estimated parameter values and standard errors for evaporative cooler models.

Case	Parameters associated with: SALINITY BETA 0/10^{-3}	SALINITY BETA 1/10^{-3}	PEOPLE BETA 2/10^{-3}	log-likelihood
1	-	-0.176±0.050	-	-119
2[a]	-	-0.173±0.054	-24±61	-118
3	410±347	-0.462±0.756	-	-120

[a] SAS LIFEREG procedure used.

SUMMARY OF ESTIMATED MODELS

In Table 16 and other tables, the number of significant figures displayed exceeds the precision with which the numbers are known so that the reader can use these numbers for computation without much further loss in precision due to rounding error. The service lives of dishwashers and humidifiers, as shown earlier, were not found to depend significantly on tap water salinity. We computed the means and standard deviations of the baseline reliability functions (Table 16), and the correlation coefficients between the two (Table 17), which are needed for estimating replacement cost and its standard error from the extreme value parameters and their correlation coefficients using propagation-of-error formulas given in Chapter 5. The correlations between the BETA parameters and the mean and standard deviation (shown in Table 18 and Table 19) are also required for estimating the standard error of replacement cost.

RESULTS OF EXAMPLE COMPUTATIONS

We used the formulas presented in Chapter 5 for the mean and standard error of lifetime estimates and models WH2 and CW1 from the present chapter to calculate estimates of mean service life plus and minus one standard error as a function of salinity for water heaters and clothes washers (Figure 10 and Figure 11). It would be misleading to plot the raw data for comparison with the model because the censored observations must be treated differently from the uncensored ones. Instead we have plotted the product-limit estimates of mean service life and its standard error.

The product-limit method cannot use any censored observation that is greater than the greatest uncensored observation. Therefore, estimates of mean service life by the product-limit method are downward biased whenever, at a given salinity level,

Table 16 Estimated parameters and standard errors for selected appliance models.

Model[a]	BETA 0/10^{-3}	BETA 1/10^{-6}	BETA 2^{b}/10^{-3}	LAMBDA	DELTA/10^{-3}
WH2	411.6 ±	-4720 ±	-	3.383 ±	399.2 ±
WH3	412.2 ±	-4705 ±	-61.75 ±	3.519 ±	391.3 ±
CW1	-	-141.9 ±	-	3.138 ±	427.0 ±
CW3	-	-138.2 ±	-172.4 ±	3.711 ±	409.6 ±
WS1	-	-190.4 ±	-	3.721 ±	525.9 ±
WS2	-	-176.2 ±	-226.0 ±	4.195 ±	469.5 ±
GD1	-	-84.64 ±	-	3.079 ±	465.9 ±
GD2	-	-92.54 ±	-123.4 ±	3.380 ±	453.5 ±
EC1	-	-176.1 ±	-	3.455 ±	463.2 ±

[a] WH1 stands for water heater case 1, etc., with CW = clothes washer, WS = water softener, GD = garbage disposer, EC = evaporative cooler.

[b] BETA2 is associated with PEOPLE except in CW3, for which it is associated with LOADS.

Table 17 Mean, standard deviation, and correlation between them for the baseline distribution of selected models.

Model	MU0 (yr)	SIGMA0 (yr)	Correlation (%)
WH2	26.13±4.05	11.16±1.81	95.22
WH3	29.95±4.87	12.56±2.13	95.76
CW1	20.43±0.92	9.268±0.721	57.51
CW3	36.28±4.71	15.87±2.42	85.28
WS1	36.63±7.82	20.05±6.43	66.13
WS2	58.75±16.43	28.99±10.46	77.50
GD1	19.25±1.42	9.446±1.209	57.74
GD2	26.01±3.37	12.44±2.09	77.08
EC1	28.03±3.32	13.67±2.72	59.54

the oldest unit still in service is older than the oldest unit observed to have failed. Several of the product-limit estimates for clothes washers were biased. If all of the

Table 18 Correlations between BETA parameters and the mean and standard deviation of the baseline distribution for selected appliance models.

Model	Parameter	Percent correlation with	
		MUO	SIGMAO
WH2	BETAO	-96.92	-94.79
	BETA1	-88.70	-82.75
WH3	BETAO	-90.58	-89.21
	BETA1	-83.66	-78.68
	BETA2	-32.22	-30.23
CW1	BETA1	-63.67	-46.09
CW3	BETA1	-35.41	-30.28
	BETA2	-94.74	-89.23
WS1	BETA1	-74.12	-55.18
WS2	BETA1	-49.32	-43.40
	BETA2	-74.15	-60.17
GD1	BETA1	-54.89	-32.94
GD2	BETA1	-29.03	-22.32
	BETA2	-82.74	-64.08
EC1	BETA1	-62.27	-42.96

product-limit estimates, including the biased ones, are weighted equally in a visual inspection of Figure 11, the accelerated-testing estimates appear to be higher than the product-limit estimates. However, if we ignore, somewhat arbitrarily, those biased product-limit estimates based on fewer than nine observed failures (shown as empty circles in Figure 11), then the product-limit estimates and the accelerated-testing estimates are closer to agreement.

Models estimated here imply longer lives and less effect of salinity on life than models estimated by Tihansky (Table 20). The lifetimes extrapolated to zero salinity are nearly twice as large as comparable figures in the work of Tihansky (which also uses exponential-plus-constant functions). By comparison with the work of Tihansky, exponential decay constants in the present work are much smaller in absolute value for clothes washers and garbage disposers, but several times higher for water heaters.

Table 19 Correlations between BETA parameters.

Model	Percent correlation between BETAi and BETAj		
	(i,j) = (0,1)	(i,j) = (0,2)	(i,j) = (1,2)
WH2	80.49	-	-
WH3	80.51	-3.420	-1.168
CW3	-	-	17.29
WS2	-	-	-2.554
GD2	-	-	-1.163

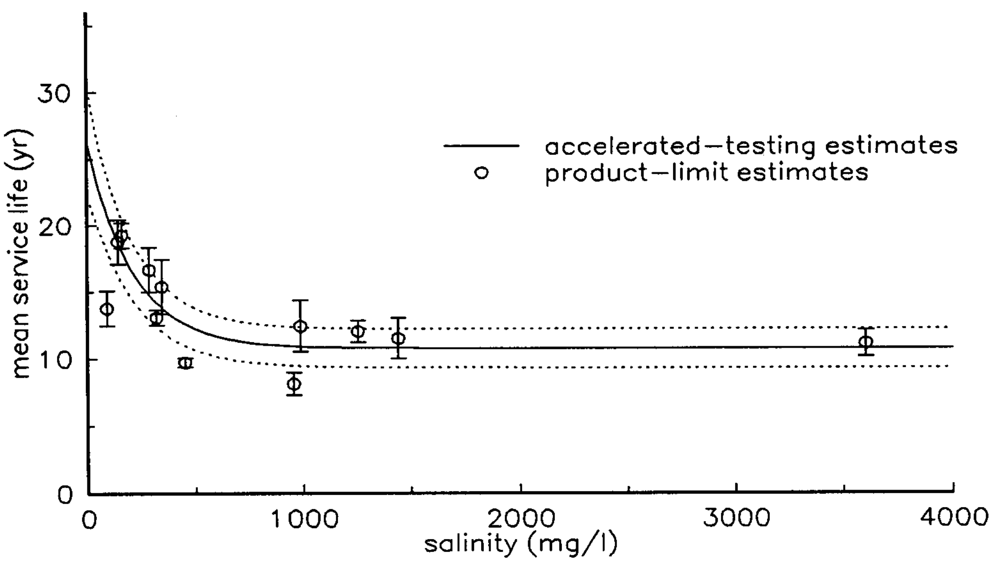

Figure 10. Mean service life and its standard error estimated by the generalized accelerated-testing model and product-limit estimates and their standard errors for water heaters as functions of salinity.

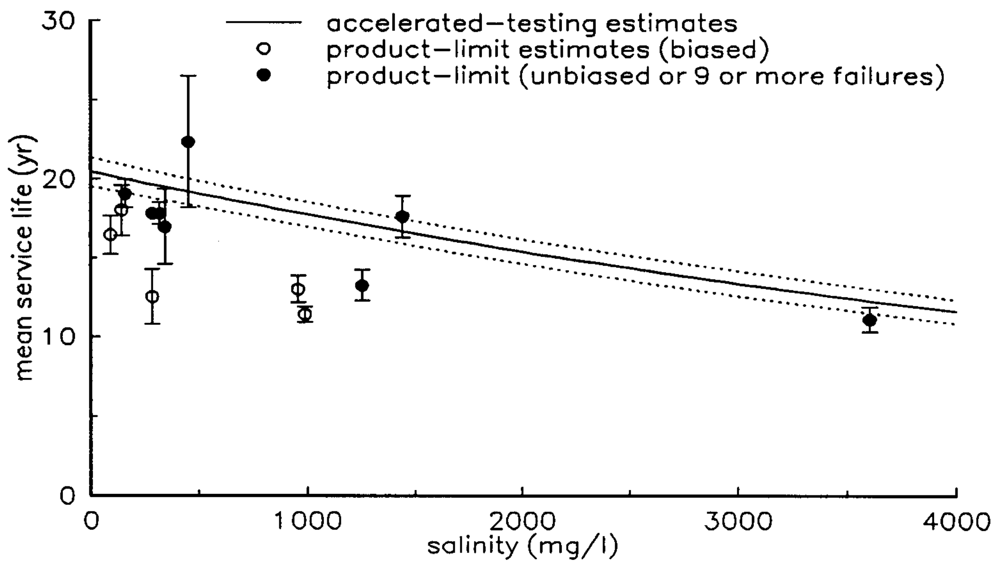

Figure 11. Mean service life and its standard error estimated by the generalized accelerated-testing model and product-limit estimates and their standard errors for clothes washers as functions of salinity.

Table 20 Comparisons of life models from the present work with those of Tihansky.

Appliance	Tihansky, 1974		Present work[a]	
	Baseline life (yr)[b]	Decay constant[c]	Baseline life (yr)[b]	Decay constant[c]
water heater	16.0	-1400	26.1	-4720
clothes washer[d]	11.1	-790	20.4	-142
garbage disposer	9.95	-1200	19.3	-84.6

[a] Models with only salinity as an environmental variable are represented.

[b] Expected life at zero salinity.

[c] The exponential decay constant has been divided by 10^{-6}. Tihansky's models are all exponential-plus-constant models; decay is to an arbitrary minimum life—five years for all three appliances. In the present work, only the water heater model is exponential-plus-constant (decaying to 10.8 years); the rest are pure-exponential.

[d] Tihansky models dish and clothes washers together. The dishwasher model in the present work does not show a significant effect of salinity.

CHAPTER 7

COST FUNCTIONS FOR APPLIANCE REPLACEMENT

Using the approximate method of Chapter 5 (applicable to cases in which the "all new" age distribution is appropriate) and the simple life models with only salinity as an environmental variable from Chapter 6, we constructed a separate cost function for each of the five appliances found to have a significant relation between salinity and service life. We constructed similar models based on a steady-state age distribution. The salinity level determines the appliance life according to the models presented in Chapter 6. The appliance life at a given salinity level determines the cost of replacement for that appliance according to the methods developed in Chapter 5. The cost functions for a given appliance are simply the estimated costs of replacement (based on two different assumptions about the initial age distribution) as functions of salinity. We constructed cost functions for each appliance based on the "all new" age distribution at three different discount rates: four percent, eight percent, and 12 percent.[23] For the steady-state age distribution, we used rates of zero percent, eight percent, and 16 percent.[24]

The cost functions implicitly assume that households adjust immediately to a change in salinity. That is, whatever behavioral differences there might be between water users at different salinity levels are assumed to be immediately adopted by water users at one salinity level upon a change in salinity to another level. Agthe and Tinney [1989] have shown that ignoring the delay in adjustment to new salinity levels implies an underestimate of the damages of increased salinity. One reason for a delay in adjustment is that appliances bought on the assumption of one salinity level might well be used after salinity changes. People may also take some time to learn about the effects of salinity and adjust their buying of nondurable goods to their new situation. For a salinity reduction, ignoring the delay in adjustment implies an *overestimate* of the benefits. The delay in adjustment works against households in either case. For a

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[23] The range of rates is intended to span a reasonable range of real discount rates based on various approaches to choosing a discount rate. The U.S. Office of Management and Budget, for example, prescribes in a 1972 circular a rate of ten percent, which "represents an estimate of the average rate of return on private investment, before taxes and after inflation" (quoted in Sassone and Schaffer [1978]).

[24] The zero percent rate corresponds to using the approximation $Ar/(\mu\rho) \approx A/\mu$. The higher rates span a reasonable range and perhaps a bit beyond. We used a coarser increment because the steady-state distribution produces a weaker dependence of replacement cost on the discount rate.

salinity increase, the detriment to households is added to costs. For a salinity decrease, the detriment is subtracted from benefits.

Another source of possible bias in the cost estimates, aside from the adjustment problems just mentioned is the failure to account for the possibility that appliance price varies with salinity. One behavioral adjustment to greater salinity might be to buy cheaper appliances that wear out sooner even if salinity is held constant. Or, people might buy more expensive appliances with better ability to withstand salinity. The cost functions estimated here are based on the contrary assumption that appliance price is independent of salinity.

For determining replacement cost it was necessary to assume prices for each appliance. Although both Sears, Roebuck and Company and the Association of Home Appliance Manufacturers were contacted, neither would provide average price information for appliances or proportional sales share for various models from which average price information could have been constructed. We resorted instead to averaging the prices listed in the Sears catalog (1992-1993 Fall/Winter Annual). Sears offers wide ranges of price and performance. Presumably, Sears offers more choices in the range of prices where the most sales are made; therefore, with luck, an unweighted average might produce something close to a sales-weighted average price. We estimated delivery and installation cost for water heaters, washing machines, and water softeners as the price quoted by the local Sears store in Fort Collins; for garbage disposers, the price of a Sears installation kit was added; the installation cost of evaporative coolers was neglected under the assumption that the buyer could do the installation with negligible expenditure of time or money (Table 21). Any sales taxes that might apply are not included because they are not costs of production but transfer payments, which should not be included in a cost-benefit analysis.

Table 21 Prices used in constructing the cost functions.

Appliance	Price ($)	Installation ($)	Total ($)
water heater	275	137	412
clothes washer	482	25	507
water softener	515	150	665
garbage disposer	127	16	143
evaporative cooler	323	-	323

REPLACEMENT COST WHEN ALL APPLIANCES ARE NEW

We calculated annual cost functions for each appliance according to the approximate formula developed in Chapter 5: $rAm/(m-1)$ where

Table 22 Total excess cost per household for appliance replacement at eight percent discount rate and its standard error as functions of salinity under "all new" and steady-state age distributions.

	"All new" age distribution		Steady-state age distribution	
Salinity (mg/l)	Cost ($/yr)	Std. error ($/yr)	Cost ($/yr)	Std. error ($/yr)
100	4.47	3.93	5.43	3.69
200	9.23	5.22	11.17	4.69
300	13.71	6.10	16.59	5.45
400	17.59	6.64	21.32	5.96
500	20.76	6.97	25.26	6.28
600	23.29	7.17	28.48	6.48
700	25.32	7.32	31.13	6.62
800	26.98	7.43	33.33	6.72
900	28.39	7.54	35.21	6.81
1000	29.61	7.64	36.86	6.88
1200	31.74	7.87	39.68	7.01
1400	33.64	8.11	42.12	7.14
1600	35.44	8.36	44.35	7.28
1800	37.20	8.61	46.45	7.41
2000	38.96	8.86	48.50	7.55
2500	43.46	9.48	53.59	7.91
3000	48.26	10.11	58.88	8.31
3500	53.45	10.74	64.53	8.75
4000	59.11	11.40	70.63	9.23

$m = e^{-\rho\mu}(1 + \rho^2\sigma^2/2)$. The separate cost functions were summed using weights equal to the fraction of households using each appliance as estimated from the household survey and, so that the total cost figure represents *excess* cost per household due to salinity, subtracted the cost at zero salinity (Figure 12 and Table 22). The advantage of excess cost is merely that it produces better graphs, particularly when costs at different interest rates are compared. The estimated annual cost at zero salinity is $26.09 per household at eight percent interest. (The cost at four percent interest is $35.20 and at 12 percent the cost is $19.35.)

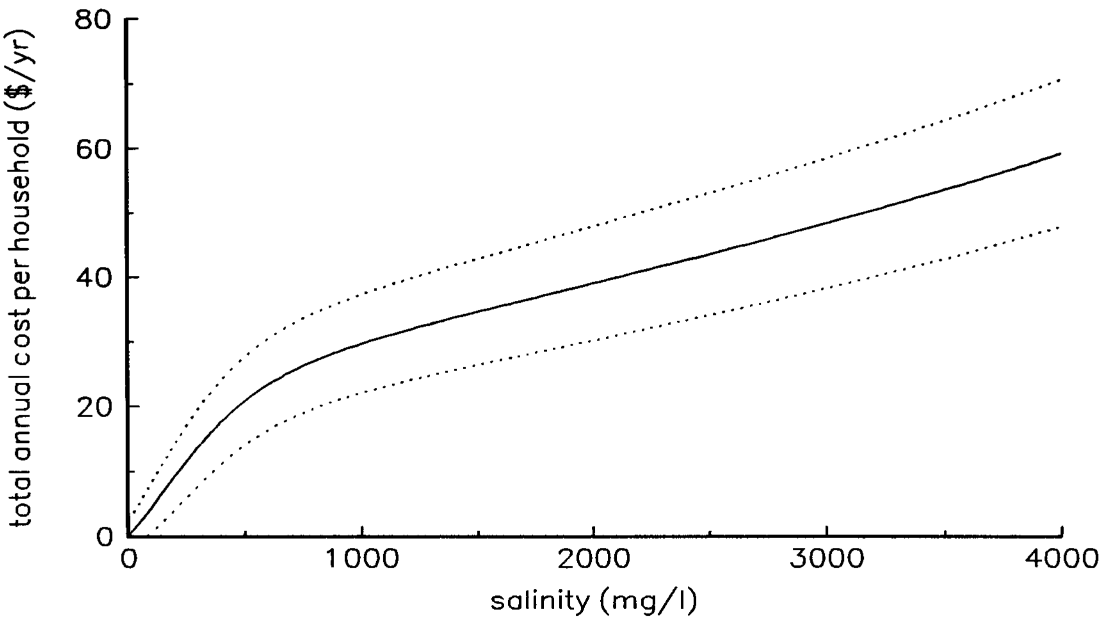

Figure 12. Total annual excess cost per household of appliance replacement (± one standard error) as a function of salinity at eight percent discount rate under the assumption that all appliances are new when salinity changes.

Estimating the fraction of households having a particular appliance was not as simple as it might have been. The survey form did not ask, for example, "which of the following appliances do you have?" Rather it asked for information such as the age of the current appliance and how long the old one lasted. Based on the interpretation of a failure to answer such a question as an indication that the respondent does not have the appliance in question, it would seem that only 83 percent of respondents have water heaters. We can be certain that virtually all of the respondents have water heaters. The questions were grouped into tables which respondents were liable to skip entirely. There were two tables, one intended to solicit information about current appliances and any repairs that might have been made to them, and one intended to solicit information about previous appliances and the purchase of new ones. Water heaters were covered first in both tables. If a respondent answered either the age of current water heater, the date repaired, or the age of old water heater, we took a failure to answer all of the same questions for another appliance to mean that the respondent did not have that appliance. If none of the questions for water heaters were answered, we did not consider the failure to answer the other questions as an indication of anything: that is, we deleted the observation from the data set for the purpose of ascertaining appliance saturation fractions. A comparison of the saturation fractions estimated as was just described with independent estimates for the United States as a whole indicates a possible overestimation of appliance saturation fractions in the present survey (Table 23).

Table 23 Saturation fractions for appliances.

Appliance	Saturation fraction	
	Present survey	Appliance, 1989[a]
water heater	assumed 100%	100%
clothes washer	91.4%	72
garbage disposer	58.8	50
evaporative cooler	51.9	-

[a] Information gathered by *Appliance* [1989] magazine from manufacturers.

For water softeners, we used a separate nonlinear least squares fit (weighted by number of households at each salinity level) to estimate the saturation fraction as a function of salinity (Figure 13). We did not allow a functional dependence for the other appliances because we found no reason to expect the use of other appliances to vary with salinity. The only other appliance that showed an obvious variation correlated with salinity was evaporative coolers. It seems obvious that the difference in evaporative cooler use is due mostly to the warmer climate in the lower valley. If the fraction of households using evaporative coolers had been allowed to vary with salinity, the differences in climate would have influenced the result in an undesirable way: if salinity were reduced in Pueblo to the level prevailing in Leadville, the residents in Pueblo would not for that reason give up their evaporative coolers. They likely would give up their water softeners.

Another way to deal with the problem of whether the use of an appliance is related to salinity or not would be to include other environmental variables: for example, a climate variable, the number of persons per household, the number of wash loads per week, and household income. We judged the benefits of such complications not worth the trouble it would take to estimate the models, construct the multidimensional cost functions, and apply the cost functions to a concrete proposal. We presented the models necessary to include number of persons per household and the number of wash loads in Chapter 6. Anyone wishing to expand the present work could use those models to construct alternative cost functions.

We propagated the standard errors estimated for the parameters of the life models to the total cost function to get an estimate of the standard error of the total

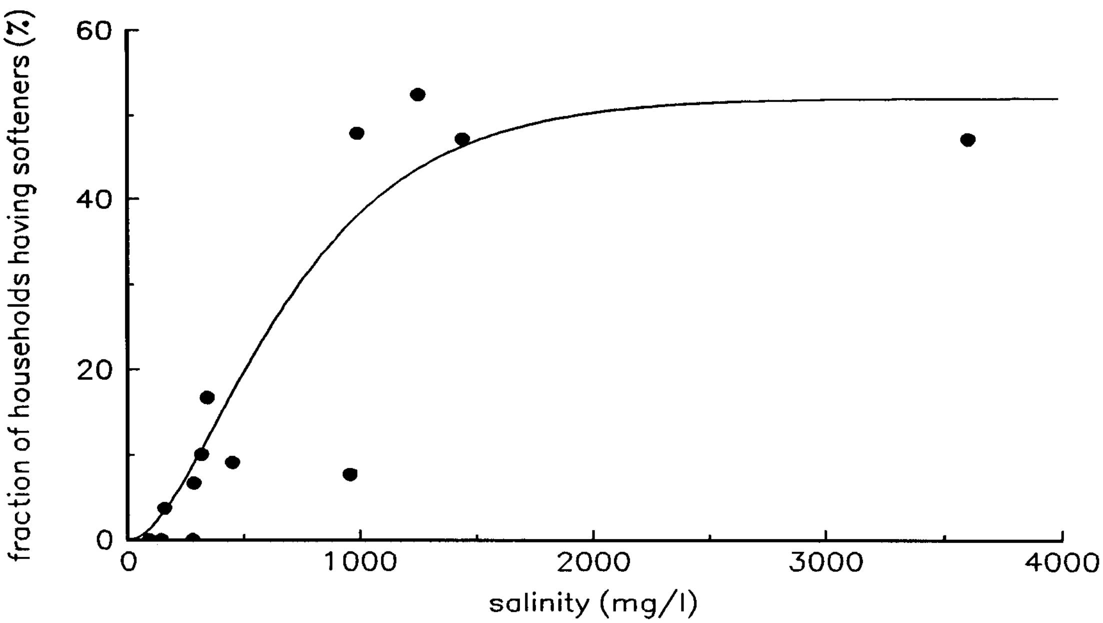

Figure 13. Nonlinear fit of fraction of households having water softeners versus salinity.

cost estimate by the formulas presented in Chapter 5 (Figure 12, and Table 22). A more complete treatment would also propagate errors from the appliance use fractions and the appliance price estimates. The standard error estimates apply to the total cost at each salinity level. For a difference in salinity, which is, of course, all we are interested in, the error should be propagated to the difference in the two cost estimates. The payoff from such calculations might not be worth the trouble, especially given that the standard error estimates rest on the shaky foundation of linear approximation of the nonlinear models. It is also possible that the acceleration models could be reformulated so that the correlations between the parameters are theoretically zero. Before investing much more time in propagating the errors in the models presented in Chapter 5 for the "all new" initial age distribution (an already tremendously complicated operation), one should investigate further the possibility of constructing models with zero correlation between parameters. Such models would greatly simplify the propagation of error calculations.

The cost function is not sensitively dependent on the interest rate, particularly when incremental changes in salinity above about 300 mg/l are considered (Figure 14, and Figure 15). What is here called the "marginal appliance replacement cost" is the derivative of the total cost curve with respect to salinity. The marginal benefit is seen to be higher for reductions in salinity below about 500 mg/l (Figure 14). The primary reason for the high marginal benefit at low salinity is that the mean life given by the water heater model depends sensitively on salinity in this range. Also much of the increased cost of a greater fraction of households owning water softeners appears in this range. Water heaters do not contribute to the cost above about 1000 mg/l, but the slow, steady contributions from the appliances modeled with a pure exponential cause a continuing rise in cost.

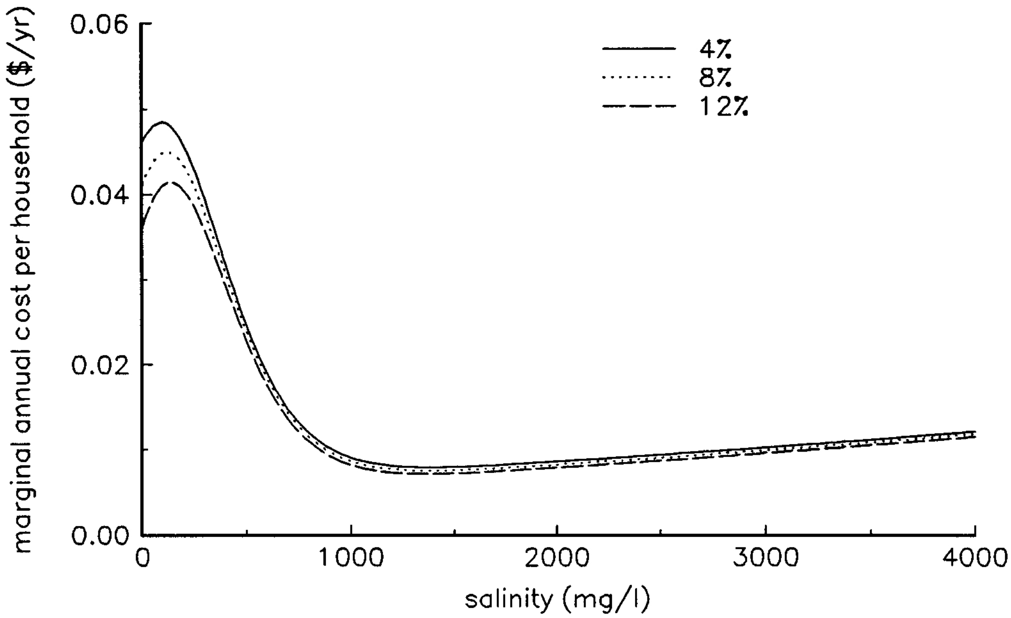

Figure 14. Marginal annual cost per household of appliance replacement at various interest rates as functions of salinity under the "all new" age distribution.

REPLACEMENT COST UNDER A STEADY-STATE AGE DISTRIBUTION

As pointed out in Chapter 6, the cost calculations are much simpler under the assumption of a steady-state age distribution than under the "all new" assumption; they should usually be more accurate as well.

We have repeated the calculations exactly as described in the previous section, except for the substitution of the far simpler cost formula $Ar/(\rho\mu)$, which applies for steady-state age distributions. The two alternative assumptions do not produce greatly different estimates at an eight percent discount rate, especially if we confine ourselves to changes above 1000 mg/l (Figure 16, Table 22). The higher the discount rate, the greater would be the divergence between the two estimates. At a discount rate of zero, the estimates would be the same. As expected, the total cost estimates under the steady-state assumption are not very sensitive to the interest rate (Figure 17). The

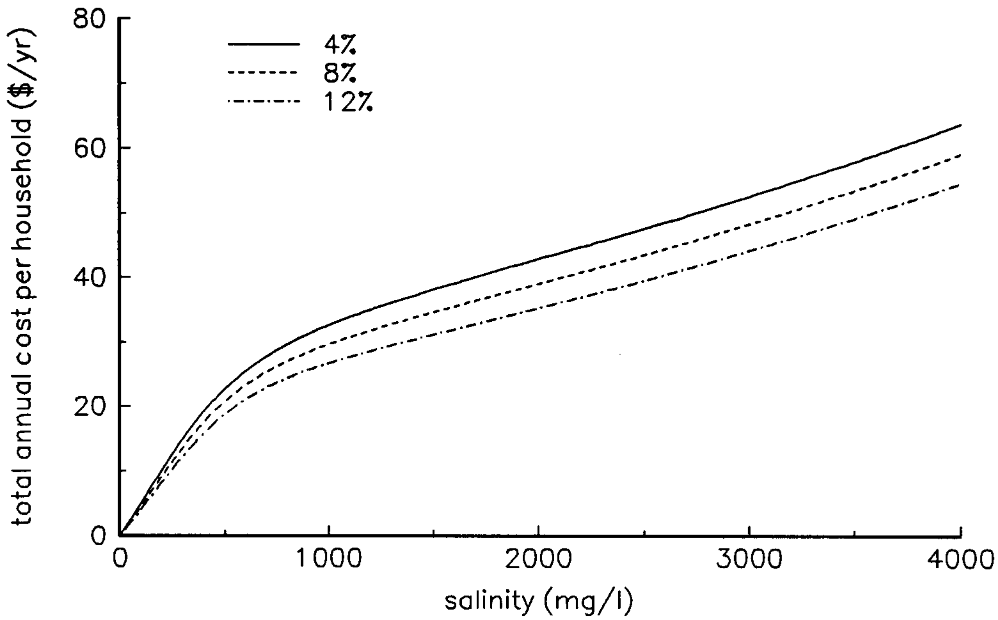

Figure 15. Total annual excess appliance replacement cost per household at various discount rates as functions of salinity under the "all new" age distribution.

same is true, of course, for the marginal cost estimates (Figure 18). The standard error estimates are slightly smaller under the steady-state assumption as compared to the estimates under the "all new" assumption (Figure 19, Table 22).

Propagation of error to the difference of two cost estimates is considerably simpler under the steady-state age distribution. However, the fact that the parameters of the life models are not independent of each other causes complications. Let us write the propagation of error formula for water heaters. The water heater model is an exponential-plus-constant model; propagation of error formulas for the other models are simply special cases of the more general model treated here.

The difference in two cost estimates (ignoring for now the discount rate, price, and saturation fractions) for the exponential-plus-constant model (adding subscripts to SALINITY to indicate two different levels) is given by

$$V(\mu_0,\beta_0,\beta_1) = \{[\beta_0 + (1 - \beta_0)\exp(\beta_1 s_b)] - [\beta_0 + (1 - \beta_0)\exp(\beta_1 s_a)]\}/\mu_0 \ . \qquad (22)$$

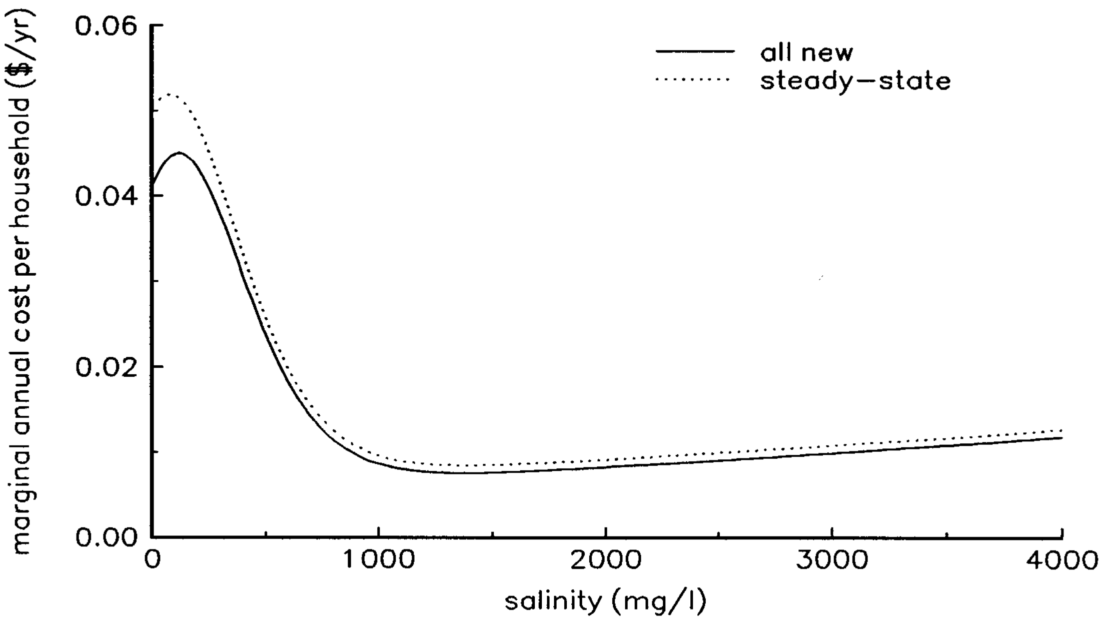

Figure 16. Comparison of marginal annual appliance replacement cost at eight percent discount rate under steady-state and "all new" age distributions.

With numerical subscripts denoting the partial derivatives of V, the propagation of error formula gives

$$S^2(V) = V_1^2 S^2(\mu_0) + V_2^2 S^2(\beta_0) + V_3^2 S^2(\beta_1) + 2V_1V_2Cov(\mu_0,\beta_0) + 2V_1V_3Cov(\mu_0,\beta_1) + 2V_2V_3Cov(\beta_0,\beta_1) \; . \tag{23}$$

Evaluate the derivatives and the formula is complete.

A similar equation is necessary for each appliance. The price times the saturation fraction times the ratio of the simple discount rate to the continuous compounding discount rate appears as a coefficient on the cost. Slight modification is required for water softeners for which the saturation fraction is not the same at each salinity level. The cost difference from each appliance is independent of the cost difference for every other appliance. Therefore, the standard error of the sum of costs for several appliances is simply the square root of the sum of the squares of the standard errors for each appliance as given by an equation like (23). We have propagated errors for differences in salinity for several possible salinity changes (Table 24).

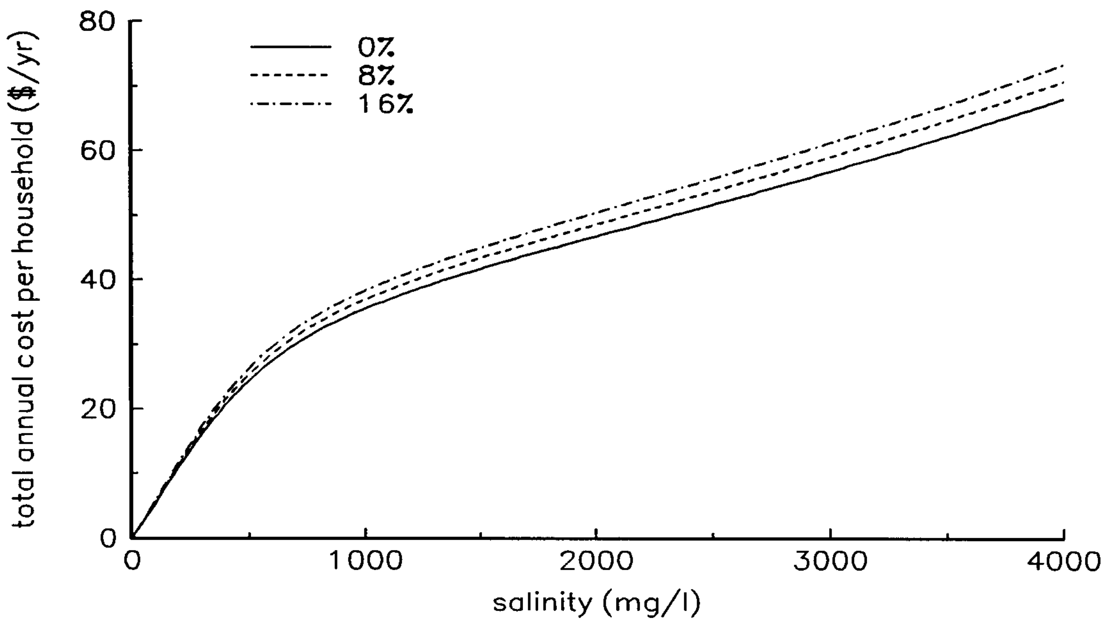

Figure 17. Effect of the discount rate on annual appliance replacement cost under the steady-state age distribution.

COMPARISON WITH LIFE MODELS FROM PREVIOUS STUDIES

Previous salinity damage studies estimated life models of appliances that can be compared with the present models on the basis of implied cost. We have taken the life models of water heaters, clothes washers, and garbage disposers used by Lohman and others [1988] and compared the total excess replacement cost as a function of salinity computed using those models with the cost computed using the presently estimated models for the same appliances (Figure 20). We used the appliance prices and saturation fractions estimated from the present work for both computations so that the comparison is strictly of the cost implications of the life models. Lohman and others did not estimate models for water softeners or evaporative coolers, so the comparison is limited to the three appliances the two studies have in common. It is clear that the two studies produced quite different results.

APPLICABILITY TO OTHER AREAS

Every salinity damage study, it seems, agonizes over the question of the effect of the individual ionic constituents of salinity. The choice is usually made to choose either salinity alone or salinity and hardness to characterize the water. We chose to consider only salinity since the correlations between the various concentrations of

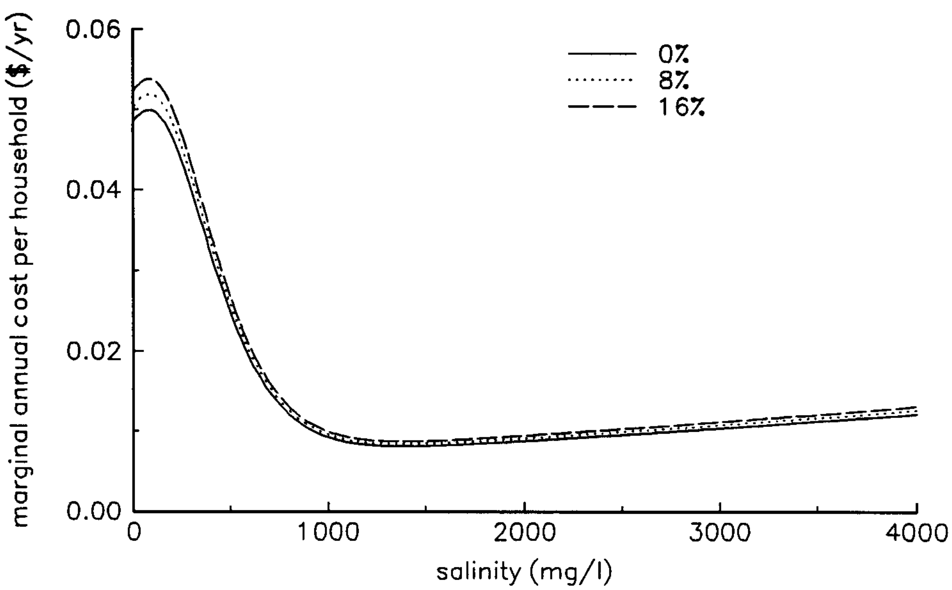

Figure 18. Effect of the discount rate on marginal annual appliance replacement cost under the steady-state age distribution.

constituents were so high. The list of possible characterizations of the mineral content of water is long: for example, sulfate, chloride, sodium, bicarbonate, carbonate, hardness, and of course, total dissolved solids, to name a few.

One way to investigate the applicability of the present results to other areas is to compare the proportional mixture of ions. For example, one could compare the ratio of total dissolved solids to hardness. D'Arge and Eubanks [1978, p. 274] state that the ratio of total dissolved solids to hardness is approximately 2.0 for Colorado River water.[25] From Coe's dissertation [1982], we have computed comparable ratios for four southern California locations: Reseda-Tarzana (2.13), Hacienda Heights (1.89), Sun City (2.28), and Blythe (2.27). We computed the ratio for three cities in the plains of the Arkansas Valley based on figures from the Colorado Department of Health [1971]. The cities and the ratios are Rocky Ford (2.00), La Junta (2.03), and Las Animas (2.34). The similar sizes of the ratio in the Arkansas Valley, the Colorado River, and Southern California (supplied in part by the Colorado River) suggest that the present results might be applicable to evaluating salinity changes in the Colorado River and Southern California. However, more work should be done to measure the

[25] D'Arge and Eubanks did not state the units of the ratio, but I assume them to be (mg/l as $CaCO_3$ per mg/l). The units as stated correspond to the most common units for stating hardness (as an equivalent concentration of calcium carbonate).

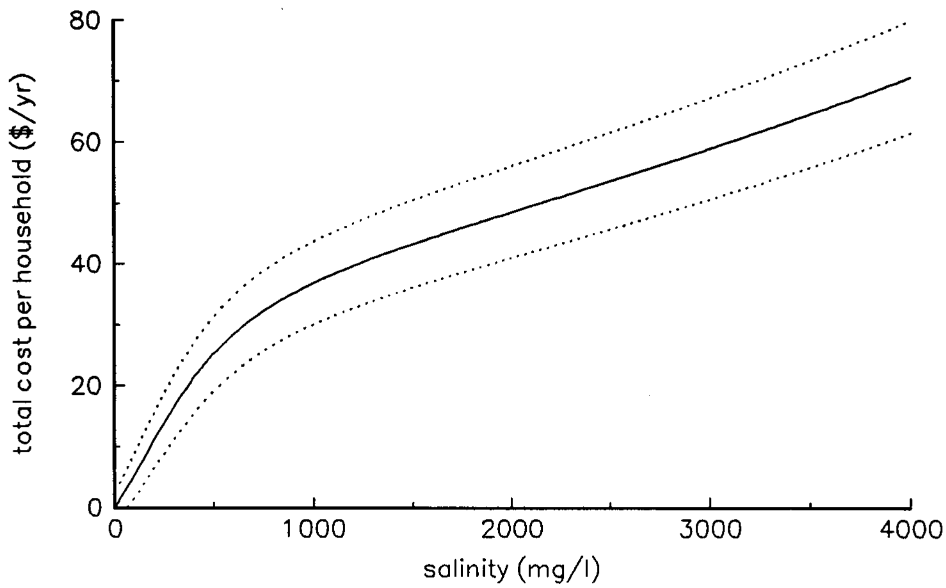

Figure 19. Total annual excess appliance replacement cost (± one standard error) as function of salinity and under a steady-state age distribution at eight percent discount rate.

sensitivity of appliance lifetimes to various individual constituents of salinity.

Results from the present study could be used to evaluate currently proposed projects in the Arkansas Valley of Colorado or as a first estimate for projects proposed or underway elsewhere. Public policy justified on the basis of earlier estimates of salinity damage, for example, the Colorado River Basin Salinity Control Project, should be reexamined in light of the present findings.

Table 24 Estimated benefit and its standard error of salinity reductions assuming a steady-state age distribution and an eight percent discount rate.

Salinity (mg/l)		Annual household benefit ($)	Standard error of benefit ($)
initial	final		
500	200	14.09	3.28
1000	200	25.68	4.76
1500	200	32.08	5.15
2000	200	37.33	5.43
3000	200	47.71	6.48
4000	200	59.45	8.56
1000	500	11.60	2.31
2000	500	23.24	3.46
3000	500	33.62	4.96
4000	500	45.36	7.49

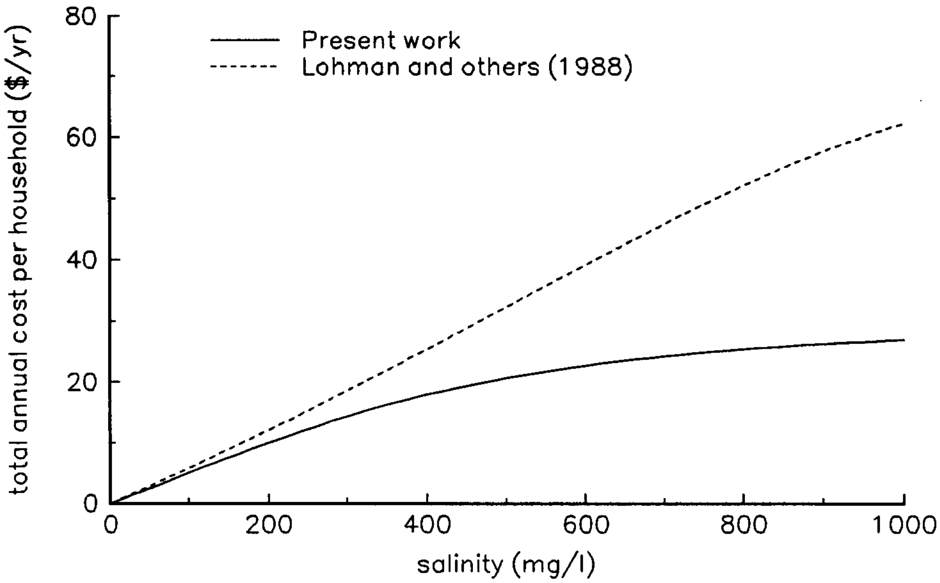

Figure 20. Comparison of estimates of cost of replacing water heaters, clothes washers, and garbage disposals with estimates based on previous studies.

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APPENDIX 1

ADDITIONAL RESULTS

This section includes additional findings that describe respondents, their homes, and their costs and practices related to water usage. Findings from the appliance repairers, plumbers, and postcard surveys are also reported.

PROFILE OF RESPONDENTS

The demographic profile of household respondents is in Table A1. The respondents were nearly equally divided by sex, male (51.8 percent) and female (48.2 percent). Nearly two-thirds had some education beyond high school. Two-fifths had incomes less than $20,000 annually, and two-thirds were in one or two person households. One of four have moved in the most recent five years. Their homes were rather old with 55 percent built 30 or more years ago.

WILLINGNESS TO PAY FOR REDUCED SALINITY

The survey described the mineral content of water and some possible problems it might cause. It then asked respondents whether they thought something should be done to lower the mineral content of their water and gave two options as responses: (1) No, mineral content is already low; and (2) Yes. We interpreted negative answers to the question as legitimate zeros. However, the two options do not cover all possible responses and a negative response could actually be a protest. A respondent might want to answer "No, mineral content is a problem, but for one reason or other I do not want anything done about it." In retrospect, it would have been better to ask something like, "Would your water supply be improved by a reduction in mineral content?" It is possible that we wrongly interpreted some protests as legitimate zeros, but, hopefully, most of the protesters registered their protests in a subsequent question which gave them that opportunity. The survey asked respondents who had answered "Yes" to estimate the amount of money they would be willing to pay as an increase in their water bills to fund a plan to provide water of "low mineral content so that scaling, staining, bad taste, and other problems associated with high mineral content no longer occur." The survey directed respondents to choose the dollar per month figure that most nearly indicated their willingness to pay for the plan from a table of values from $0 to $58 in increments of $2. We used a subsequent question asking why zero was circled to eliminate protest zeros. There was an obvious association between salinity and willingness to pay to reduce it (Figure A1).

Table A1 Profile of respondents and their homes (household survey)

Characteristic	Number	Percent	Cumulative %
respondent gender			
male	353	51.8	51.8
female	259	48.2	100.0
respondent education			
≤ 8 years	41	5.9	5.9
9-11 years	50	7.2	13.2
high school	168	24.3	37.5
some college	231	33.5	71.0
bachelor's degree	129	18.7	89.7
> bachelor's degree	71	10.3	100.0
respondent income (1990)			
< $20,000	258	41.0	41.0
$20,000-24,999	84	13.3	54.3
$25,000-34,999	109	17.3	71.6
$35,000-49,999	94	14.9	86.5
≥ $50,000	85	13.5	100.0
household size			
one	153	21.7	21.7
two	321	45.2	66.9
three	112	15.8	82.7
four	86	12.1	94.8
≥ five	37	5.2	100.0
year moved to home			
pre-1955	79	12.9	12.9
1955-1964	86	14.1	26.9
1965-1974	108	17.6	44.5
1975-1984	178	29.0	73.5
post 1984	163	26.5	100.0
age of home			
≥ 50 years	188	27.8	27.8
40-49 years	57	8.4	36.2
30-39 years	127	18.8	54.9
20-29 years	84	12.4	67.4
11-19 years	141	20.8	88.2
6-10 years	54	8.0	96.2
≤ 5 years	26	3.8	100.0

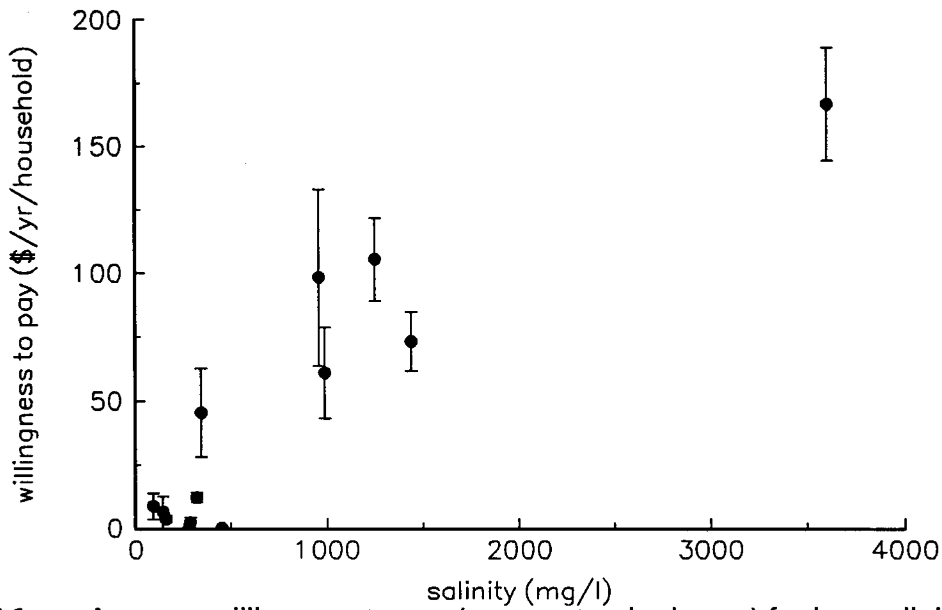

Figure A1. Average willingness to pay ($\pm$ one standard error) for low salinity water as an addition to current water charges versus salinity.

RESPONSES TO OTHER QUESTIONS

Expenditures on bottled water

The average household consumption of bottled water increased dramatically with salinity above about 1000 mg/l (Figure A2). One of the averages (for Park Center, in Canon City) is something of an outlier. Its standard error is also several times higher than most of the other standard errors. Park Center draws water from an artesian well with comparatively high salinity, about 960 mg/l. The city water has a salinity of only about 160 mg/l. According to comments by respondents who receive Park Center water, the city water is cheaper and of much better quality. The water quality and price differences are a source of bitter complaints by respondents. A clearer picture of the relationship between salinity and annual household expenditures for bottled water emerges if the outlier is removed (Figure A3).

Car radiators

The fraction of households reporting using tap water in their car radiators decreased from around 75 percent at low salinity (below 900 mg/l) to 30 or 40 percent at higher salinity (Figure A4). The fraction reporting use of bottled water mixed with antifreeze increased from five or ten percent at low salinity to around 30 percent at high salinity. The remaining approximately constant fractions of respondents (except for two) used pure antifreeze or did not know what was used in their radiators.

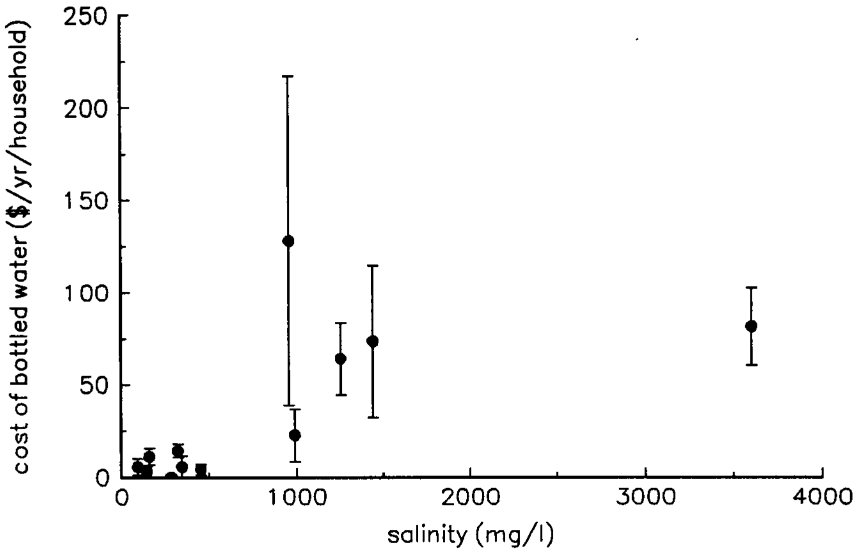

Figure A2. Average expenditure on bottled water (± one standard error) versus salinity (full sample).

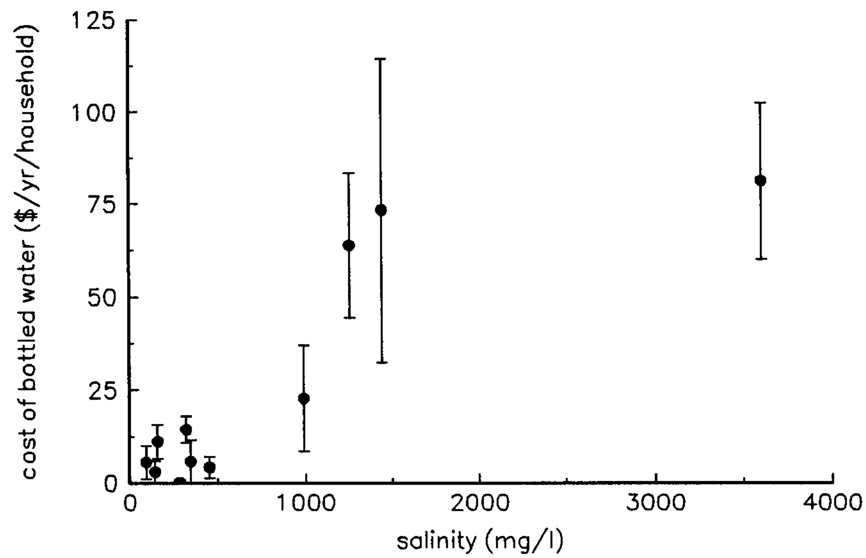

Figure A3. Average expenditure (± one standard error) on bottled water versus salinity (Park Center omitted).

Evidently many residents of the Arkansas Valley are aware of possible problems with using tap water in car radiators and respond by using bottled water instead.

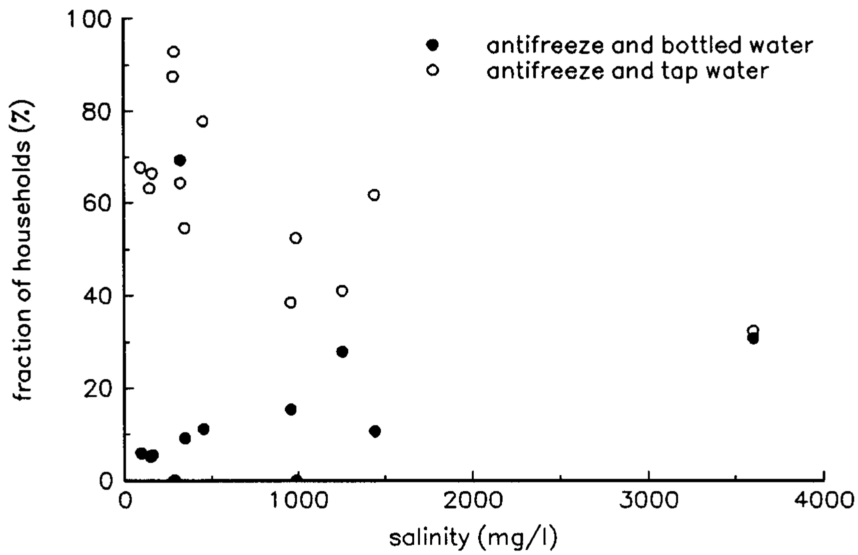

Figure A4. Fraction of households using mixtures of antifreeze and (1) bottled water and (2) tap water versus salinity.

Laundry detergent

There is a statistically significant relationship (at the .05 level) between salinity and the amount of detergent residents reported using for laundry. However, the relationship is trivial--amounting to just a tenth of a cup per wash load over the entire range of salinity from 0 to 4000 mg/l (Figure A5).

Comparing willingness to pay with expenditures

The sum average expenditures on bottled water and estimated appliance repair costs are approximately equal to average willingness to pay (Figure A6). We also collected data on other costs such as cost of plumbing and appliance repair, cost of cleaning deposits from fixtures and operating cost of water softeners (salt consumption, for example) and reverse-osmosis appliances (membrane replacement). The comparison implied in Figure A6 suggests that costs other than for bottled water and appliance repair can probably be ignored. Of course, there is no guarantee that the willingness-to-pay figures and the sum-of-cost figures must match. Whether the two are equal depends on accuracy in measurement (on our part) and accuracy in perception by householders. The possibility also remains that further examination of our data on other costs would uncover important contributions to the total cost.

Also noteworthy is that a rough comparison of marginal salinity damage (Figure A6) indicates that the damages are much lower than most previous estimates. According to a summary of previous salinity damage estimates by Booker [1990, p.

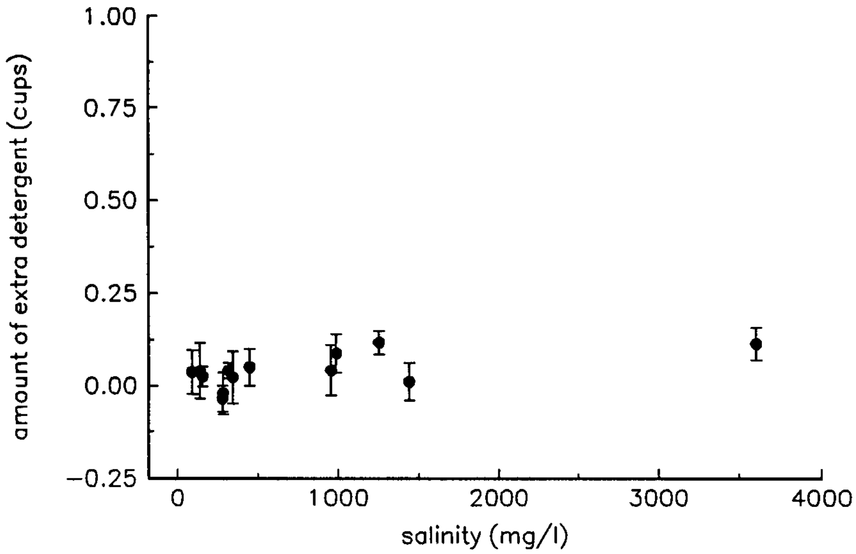

Figure A5. Average amount of detergent (± one standard error) used in excess of recommended amount versus salinity level.

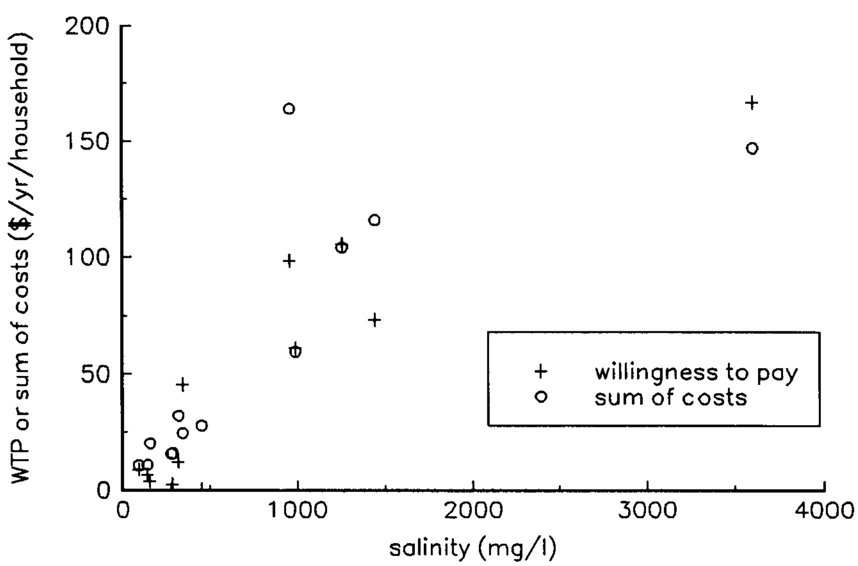

Figure A6. Comparison of average willingness to pay with the sum of average bottled water expenditures and estimated appliance replacement cost.

51] estimated annual marginal damage per household ranges from 0.11 $/(mg/l) [McGuckin, 1977] to 0.48 $/(mg/l) [Lohman and others, 1988] with three estimates clustered around 0.27 \$/(mg/l).[26] However, between zero and 1500 mg/l, the cost of increased salinity indicated by Figure A6 rises to about \$100. The estimated marginal damage in the range to 1500 mg/l is therefore in the neighborhood of 0.07 \$/(mg/l): about 15 to 60 percent of previous estimates.

Extra time spent in various activities associated with increased salinity

The responses to the question about extra time spent in activities such as cleaning fixtures, doing laundry, and other activities possibly associated with salinity (question 5) show clear relationships to salinity (Figure A7, Figure A8, Figure A9, and Figure A10). However, on reexamination of our questionnaire, we realized that the question was not posed properly. We asked, "Does the quality of your water increase the work/chores around home? If so, circle about how many extra hours per week you or others have to work because of poor water quality?" In retrospect, it is clear to us that we should not have referred to "extra work" but should have asked respondents to estimate the total time they spend at various activities. The reference to extra work requires the respondents to know how much time they would spend if water quality were not "poor." It is possible that respondents, not being able to answer the questions thoughtfully, merely treated them as general questions about water quality. In general, in designing our questionnaire, we endeavored to avoid asking respondents to make judgements about the effects of their water in comparison to other water or some standard of water quality. (In the case of willingness to pay, such a reference was unavoidable.) The reference to "extra time" could have been avoided, and in our judgement, should have been. For this reason, we can not confidently make quantitative inferences from question 5. However, the responses give some evidence that salinity may impose a significant cost in time spent at the various activities. It would be helpful if future studies could address, in a more adequate fashion, the question of the salinity-related cost of time spent in the various activities.

SURVEY OF APPLIANCE REPAIR FIRMS

The questionnaire sent to appliance repair firms contained 11 questions asking about water quality in the community, appliance repair histories, and service lives of appliances with regard to customers on the local municipal water supply. Results of the survey indicated most of the 21 firms had their business in the current community for ten years or less. Two companies had been in the community over 50 years.

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[26] Booker produced one of these from the report by Lohman and others by ignoring car "radiator damage and other factors."

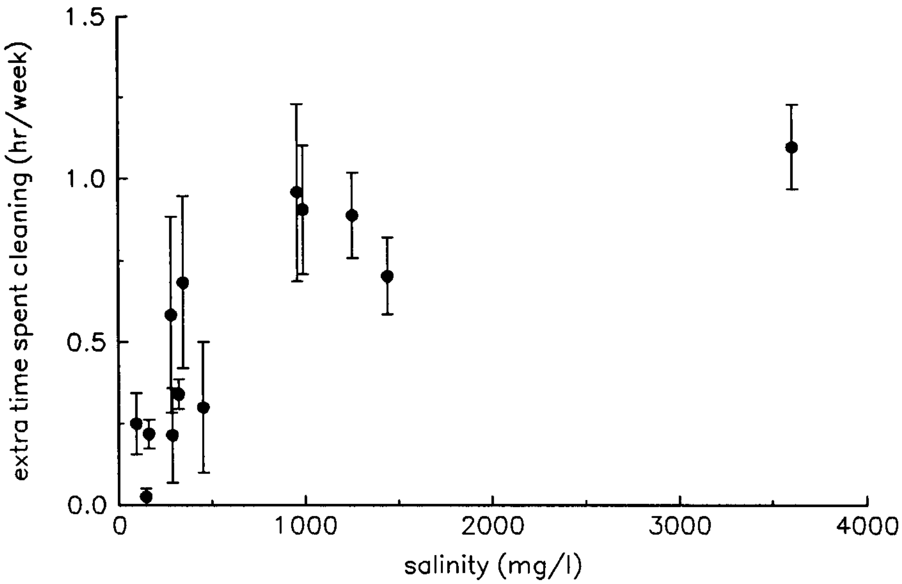


Figure A7. Mean extra time spent cleaning versus salinity.

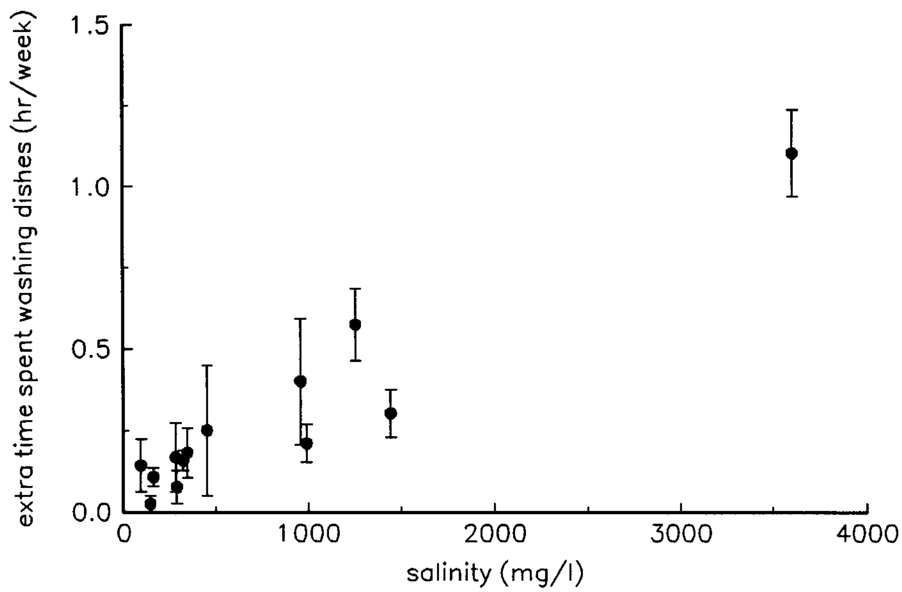


Figure A8. Mean extra time spent washing dishes versus salinity.

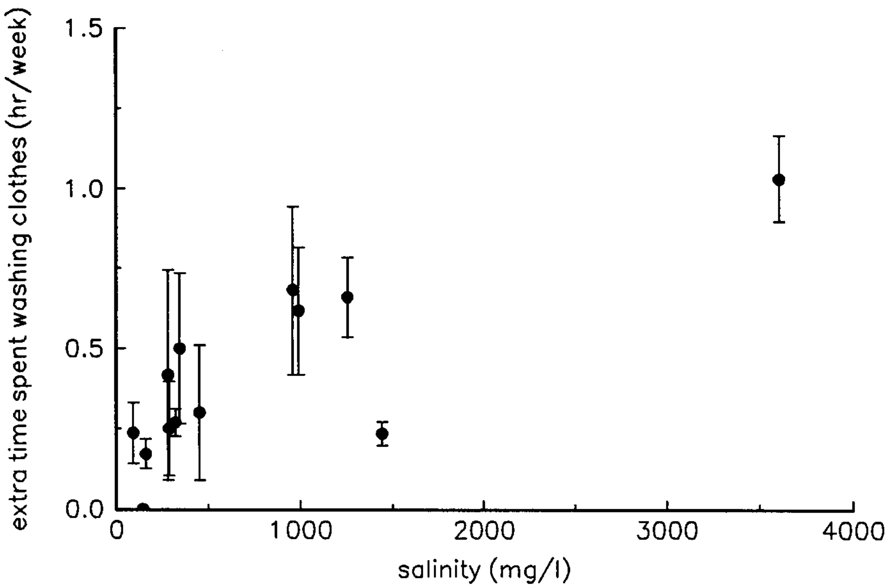


Figure A9. Mean extra time spent washing clothes.

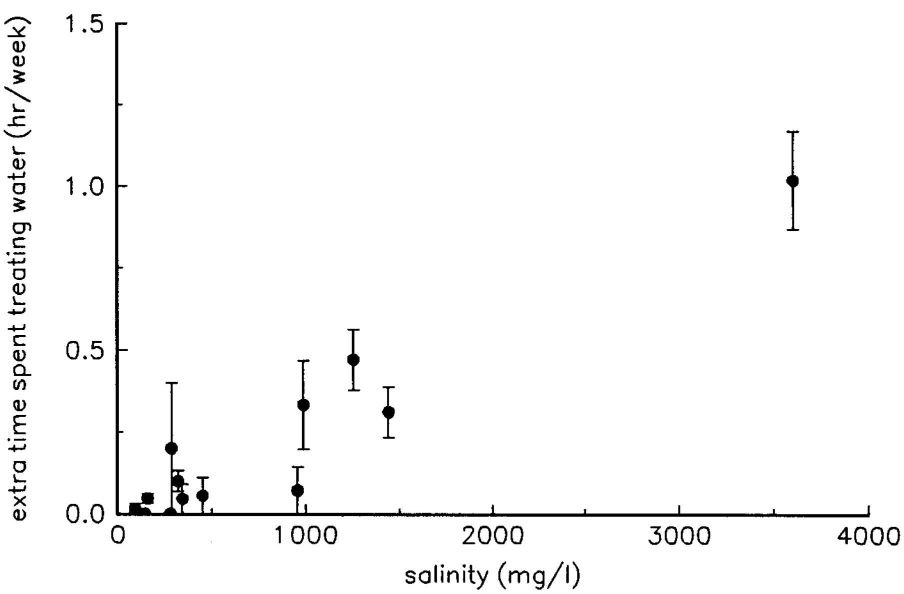


Figure A10. Mean extra time spent treating water.

Table A2 Appliance repairers and plumbers rate the quality of community's domestic water supply

Rating	Appliance repairers (#)	Plumbers (#)
excellent	4	4
good	8	6
fair	7	6
poor	2	3
total	21	19
improved	4	3
no change	15	12
gotten worse	2	4
total	21	19

Water quality

Twelve appliance repair firms reported the quality of community's domestic water supply as excellent or good and nine rated it as fair or poor (Table A2). As to change in quality, 15 firms indicated the quality of water had not changed in the last three years, but two firms said it had gotten worse. When asked about the effects of water quality on household piping, fixtures, and water-using appliances, the mean scale was 2.57, 3.48, and 3.48 for the effects of corrosive, scaling, and stains, respectively, with 1 = most desirable quality and 5 = least desirable (e.g., corrosive). Among 21 appliance repair firms, 14 indicated ten percent or less of customers' homes using water from private wells.

Appliance repair histories

Table A3 indicates that water-related and mechanical problems were cited equally as the most frequent cause of appliance repair. Corrosion was the most frequent problems for gas water heaters, while electric water heaters had more scaling problems. Appliances with motors (dishwasher, washer, garbage disposal) had more mechanical than water-related repairs.

Among six appliances, evaporative coolers had the highest number of service calls and water heaters had the lowest number of service calls (Table A4). As the average repair cost for each appliance, washers had the highest at $53 dollars, a range from 25 to 80 dollars. Gas water heaters had the lowest average repair cost ($33).

Table A3 Appliance repair histories

Appliance	Most frequent cause of repair identified					
	Corrosion	Scaling	Water-related total	Mech-anical	All total	Other
water heater (electric)	*6*	*6*	*12*	*5*	*17*	
water heater (gas)	*8*	*4*	*12*	*3*	*15*	*bad control not cleaned*
evaporative cooler	*5*	*5*	*10*	*5*	*15*	
dishwasher	*4*	*3*	*7*	*12*	*19*	
washer	*3*	*2*	*5*	*14*	*19*	
garbage disposal	*3*	*2*	*5*	*12*	*17*	*motor windings*
total	*29*	*22*	*51*	*51*	*102*	

Service lives of appliances

When asked about appliance replacements, repairers indicated that most replacements were due to mechanical problems (Table A5). Among six appliances, electric water heaters, gas water heaters, and evaporative coolers had most corrosion problems causing replacement.

For appliance mean service life (Table A6), evaporative coolers were reported as the most durable with an average of approximately 13 years at age of replacement. Gas water heaters and electric water heaters were estimated to have equal mean service lives of about 11 years each.

Although appliance repair firms were asked if they usually removed the sacrificial anodes from water heaters, only one firm reported doing so, indicating that replacing the anodes extended service life. The useful life of the sacrificial anodes was in the range of one to 20 years, and the mean life was eight years (Table A7). According to appliance repair firms' estimation, gas water heaters typically were replaced when 12 years old and electric water heaters when 11 years old if anodes were replaced. Estimates of service life of a heating element for electric water heaters was an average of eight years.

Table A4 Number of appliance service calls and average cost of call

Appliance	Number of calls	#	Average cost ($)	Range ($)
water heater (electric)	≤ 2	9		
	3-5	2	49.30	25.00-80.00
	≥ 6	1		
water heater (gas)	≤ 2	12	33.40	17.50-65.00
	3-5	1		
evaporative cooler	≤ 2	5		
	3-5	3	39.60	20.00-75.00
	≥ 6	6		
	no response	1		
dishwasher	≤ 2	9		
	3-5	8	47.00	30.00-80.00
	≥ 6	1		
	no response	1		
washer	≤ 2	3		
	3-5	13	52.50	25.00-80.00
	≥ 6	2		
garbage disposal	≤ 2	11	43.20	15.00-180.00
	3-5	2		

SURVEY OF PLUMBING CONTRACTORS

The questionnaire sent to plumbing contractors asked 14 questions related to water quality in the community, water and wastewater piping replacement and repair, fixture and appliance replacement, and sacrificial anode replacement. Nineteen questionnaires were usable for this study. Five respondents had been in business for ten years or less in the community, and two contractors for 36 years or more.

Water quality

Ten plumbers rated the quality of community's domestic water supply as excellent or good; nine reported it as fair or poor (Table A2). Regarding their opinion on the change in quality of water in the last three years, 12 reported no change and four contractors indicated it had gotten worse. When describing effects of water

Table A5 Estimated service lives of appliances (by repairers)

Appliance	*Most frequent cause of replacement*					
	Corrosion	*Scaling*	*Water-related total*	*Mech-anical*	*All total*	*Other*
water heater (electric)	*9*	*4*	*13*	*2*	*15*	*rusted*
water heater (gas)	*11*	*2*	*11*	*2*	*13*	*rusted*
evaporative cooler	*11*	*0*	*11*	*2*	*13*	*rusted*
dishwasher	*6*	*1*	*7*	*11*	*18*	*pump/motor failure*
washer	*4*	*0*	*4*	*14*	*18*	*transmission failure*
garbage disposal	*4*	*1*	*5*	*10*	*15*	*motor windings*
total	*25*	*8*	*33*	*41*	*74*	

quality on household piping, fixtures, and water-using appliances, the mean scales were 3.24, 3.68, and 2.61 for effects of corrosion, scaling, and stains, respectively (1 = most desirable quality and 5 = least desirable). Most contractors reported that ten percent or less of homes in the community used water from private wells.

Table A6 Estimated average mean service life (by repairers)

Appliance	Number of firms	Average age when replaced (years)
water heater (electric)	18	11.10
water heater (gas)	19	10.60
evaporative cooler	15	12.50
dishwasher	19	8.90
washer	19	9.70
garbage disposal	16	9.60

Table A7 Sacrificial anodes replacement related to water heater (by repairers)

Service life	Years	
	Range	Mean
sacrificial anodes	1-20	7.78
if anodes replaced, water heaters typically last		
gas	5-20	12.38
electric	5-20	11.00
heating element (electric water heater)	3-18	8.43

Water piping system replacement and repairs

Copper water pipe had the highest total replacement cost, ranging from 500 to 1,500 dollars (Table A8), while plastic pipe had the lowest replacement cost, ranging from 600 to 900 dollars. Among five types of pipe, galvanized steel pipe was most commonly used in replacing household water piping. However, the galvanized steel pipe was most in number of repairs; the average repair cost was 145 dollars, ranging from 15 to 800 dollars (Table A8).

Wastewater piping replacement and repairs

Galvanized steel and cast iron wastewater pipes were most used in replacing household wastewater pipes by piping contractors, but they were the most expensive pipes (Table A9). The replacement cost of cast iron was as high as 5,000 dollars and galvanized steel as high as 1,500 dollars. Both types of wastewater pipes were reported as having longer service lives. For wastewater piping repairs, the average cost of copper pipe was highest at 122 dollars, ranging from 20 to 400 dollars (Table A9).

Fixtures and appliances replacement

Table A10 indicates the average age of replaced fixtures and appliances in households. Plastic kitchen faucets had the shortest life, six years, while the average life of toilets, 22 years, was the longest.

Table A8 Piping systems' replacement and repair with costs (by plumbers)

Type of pipe	Number	Age at replacement (years)	Average cost ($)	Range ($)
galvanized steel	1	15	700	
	2	20	350	200-500
	4	25	750	400-1,000
	1	30	200	
	1	35	800	
	3	40	617	250-800
	3	50	683	450-1,000
copper	3	10	867	500-1,500
	3	25	750	500-1,000
	1	50	200	
plastic	1	5	250	
	2	10	750	600-900
	1	15	250	
	1	40	150	
lead	1	60	800	
polybylene		NA	NA	

Sacrificial anodes replacement versus water heater

No plumbing contractors reported installing water heaters or removing sacrificial anodes from water heaters. However, seven reported that replacing the anodes would extend service life of water heaters, five said it would not extend the life. The average useful life of sacrificial anodes was six years, with range from two to 15 years reported (Table A11). In addition, plumbers estimated the average service life of a heating element for an electric water heater was four years.

POSTCARD STUDY

To examine the question of whether household nonrespondents were similar to or different from respondents, a postcard questionnaire was developed. The postcard contained ten questions which were unnumbered to conserve space. The first question asked for rating of local water quality from excellent to poor, and the remaining questions were taken from the mail questionnaire. Repairs and their cost for water-using appliances and replacements in the last two years were requested. Piping

Table A9 Wastewater piping replacement and average cost (by plumbers)

Type of pipe	Number	Age at replacement (years)	Average cost ($)	Range ($)
galvanized steel	1	10	1,000	
	1	25	600	
	4	30	875	200-1,500
	3	50	567	500-600
	1	70	1,200	
copper	1	10	1,000	
	2	20	773	145-1,400
	3	30	733	600-1,000
	2	35	825	800-850
	1	40	500	
plastic	2	10	245	90-400
	1	25	750	
	1	40	1,000	
	1	50	200	
cast iron	1	15	1,500	
	1	20	500	
	1	25	600	
	2	30	850	800-900
	1	40	1,500	
	1	45	350	
	2	50	3,000	1,000-5,000
	2	60	950	800-1,100
lead	1	30	800	
	2	40	800	600-1,000
clay	1	50	600	

material used in the water system was requested. A Yes/No response question asked if the mineral content of the tap water should be reduced. Source of the household water supply (city/town, well, etc.) was to be identified. Demographics included household size, years in present home, zip code, and highest level of education.

Procedures, return, and response

The postcard questionnaire was sent to 515 households that had not responded to "Water in Your Community: Quality and Cost" after 11 weeks. The households

Table A10 Estimated lifetime of house fixtures and appliances

Fixture	Plumbers (#)	Type	Average age when replaced (years)
kitchen sink	*19*	*enameled metal*	*14.6*
	18	*stainless steel*	*15.6*
kitchen faucet	*19*	*brass or copper*	*14.3*
	17	*plastic*	*6.4*
shower stall	*18*	*plastic*	*11.2*
toilet	*18*		*21.9*
toilet flushing mechanism	*19*		*8.0*
sink faucet (lavatory)	*14*	*brass or copper*	*12.7*
	17	*plastic*	*7.1*
shower head	*13*	*brass or copper*	*7.2*
	18	*plastic*	*5.2*
shower or bath faucet	*19*	*brass or copper*	*15.6*
	18	*plastic*	*7.2*
water heater	*19*	*gas*	*9.2*
	19	*electric*	*8.5*
lawn sprinkler system	*9*		*16.4*

Table A11 Sacrificial anodes replacement related to water heaters (by plumbers)

Service life	Years	
	Range	Mean
sacrificial anodes	2-15	5.71
if anodes replaced, water heaters typically last		
gas	5-25	11.54
electric	5-25	12.18
heating element (electric water heater)	2-15	4.44

selected were every second nonrespondent. Of 515 postcard questionnaires sent, 111 returns were useable, 19 were undeliverable, four were overt refusals, and the remaining 381 were nonreturns. This represents a response rate of 22 percent. The respondents are referred to as the postcard group in subsequent discussion.

Findings

Three questions explored water source and quality. When postcard respondents were asked to rate the quality of water in their local area, 12 percent of the respondents rated it excellent, 42 percent said good, 21 percent responded fair, and 21 percent rated it poor (Table A12). Generally, the postcard group indicated higher quality water than the full survey respondents. Postcard respondents' source of household water was city water (76 percent), nine percent subdivision well, 14 percent household well, and one percent other. In assessing tap water quality, 51 percent responded "Yes" something should be done, and 39 percent said nothing should be done to lower the mineral content. Ten percent did not respond.

Table A12 Postcard respondents' views on quality and source of water

Quality	Postcard		Full Survey	
	$	%	#	%
excellent	13	11.7	107	15.1
good	47	42.3	308	43.4
fair	23	20.7	167	23.5
poor	23	20.7	117	16.5
no response	5	4.5	11	1.6
total	111	99.9	710	100.1
Source				
city/town	84	75.7	643	90.6
subdivision well	10	9.0	13	1.8
own well	15	13.5	20	2.8
other	1	0.9	4	0.6
no response	1	0.9	30	4.2
total	111	100.0	710	100.0

Repairs and replacements for water-using appliances in the last two years were requested. In addition, piping material used in the home was requested. Eighty percent of the postcard sample reported no repairs for appliances in the last two years. Among those who reported appliance repairs, the most frequent was water heaters (Table A13). Second was washers. In comparing the appliances replaced, water heaters and washers were most reported. For the piping material used in the home's water system (Table A14), copper water pipes were most frequently found (31 percent), and 21 percent reported plastic pipes.

Table A13 Appliance repairs and replacements (postcard respondents)

Appliance	Replacements		Repairs	
	#	%	#	%
water heater	19	17.1	5	4.5
washer	6	5.4	4	3.6
dishwasher	5	4.5	2	1.8
toilet	2	1.8		
ice maker	1	0.9		
water pump	1	0.9		
water faucet	1	0.9		
pipes	1	0.9	1	0.9
coffeemaker	1	0.9		
no response	74	66.7	99	89.2
total	111	100.0	111	100.0

Demographic characteristics (Table A15) included education level, household size, and years of residence in present home. Forty percent of the sample were high school graduates. The second most frequent level at 19 percent was some college. Twenty percent had a bachelor's or higher college degree.

Fifty-nine percent of the sample lived in households of one or two persons. Twenty-one percent had four or more persons in their households. More than one-third of the sample, 34 percent, reported living five or less years in the present home. On the other end of the range, seven percent had lived in their present homes for 40 years or more.

Table A14 Piping material used in home water system (postcard respondents)

Pipe Material	Number	Percent
plastic	23	20.7
copper	34	30.6
iron	15	13.5
plastic & copper	17	15.3
copper & iron	8	7.2
plastic & iron	5	4.5
plastic, copper, & iron	4	3.6
other	1	0.9
no response	4	3.6
total	111	99.9

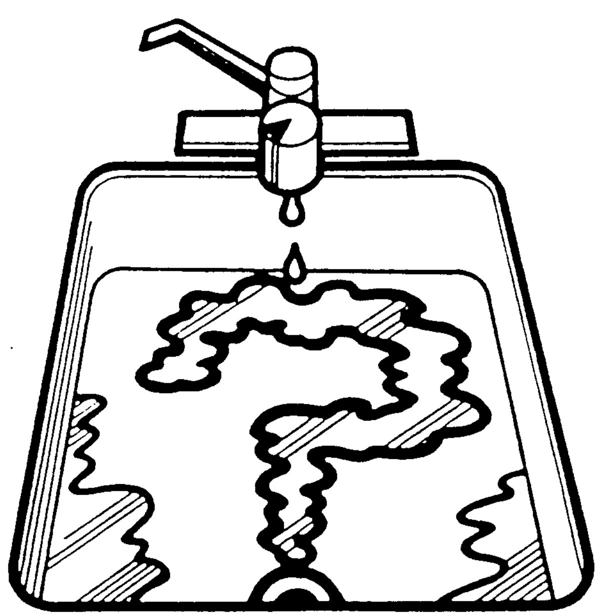
Table A15 Demographic characteristics (postcard respondents)

Characteristic	Number	Percent
education level attained		
grade school	12	10.8
high school	44	39.6
some college	21	18.9
bachelor's	17	15.3
master's	5	4.5
no response	12	10.8
total	111	99.9
household size		
one	20	18.0
two	46	41.4
three	22	19.8
$\geq$ four	23	20.7
no response	0	0.0
total	111	99.9
years lived in present home		
1-5	38	34.2
6-10	19	17.1
11-20	22	19.8
21-40	23	20.7
$\geq$ 40	8	7.2
no response	1	0.9
total	111	99.9

APPENDIX 2

QUESTIONNAIRES

Water in Your Community: Quality and Costs



☼ A STUDY OF WATER AND MINERAL CONTENT ☼

☼ THE ARKANSAS RIVER ☼

Your help with this effort is greatly appreciated!
Please use the back page for comments or to add detail.
Thank you!

WATER

1

1. **How do you rate the quality of water in your local area? Check (✓) your response.**

____ Excellent
____ Good
____ Fair
____ Poor

2. **In your opinion, how has the quality of water in the local area changed in the last three years? Check (✓) your response.**

____ Improved
____ No change
____ Gotten worse

3. **Describe the quality of water in your home. Please place a check (✓) on one blank in each line that describes how your water usually is.**

Example

Rusty	____	____	____	✓	____	*No Rust*

Clear	____	____	____	____	____	Cloudy
Hard	____	____	____	____	____	Soft
Smells	____	____	____	____	____	No Smell
Poor Taste	____	____	____	____	____	Good Taste
Stains/Discolors	____	____	____	____	____	No Discoloration/Stains
Leaves Film	____	____	____	____	____	No Film
Leaves Scale (hard, rough)	____	____	____	____	____	No Scale
High Mineral Content	____	____	____	____	____	Low Mineral Content

4. **Water can affect many items and daily activities. Indicate if the water piped into your home affects each of the items listed on the left. Circle (○) the best response in each line.**

	YES, IT DOES	NO, IT DOESN'T	NOT SURE	DO NOT HAVE
Discolors/pits:				
pots and pans	Y	N	NS	DNH
coffeemaker	Y	N	NS	DNH
teakettle	Y	N	NS	DNH
Clothes (when washed)				
look gray	Y	N	NS	
stain/spot	Y	N	NS	
feel rough	Y	N	NS	
don't seem to get clean	Y	N	NS	
wear out faster than they should	Y	N	NS	
Water makes cleaning more difficult				
tub/shower	Y	N	NS	DNH
walls of shower/tub	Y	N	NS	DNH
toilet bowl(s)	Y	N	NS	DNH
sinks	Y	N	NS	DNH
dishes	Y	N	NS	DNH
Water causes problems with				
steam iron	Y	N	NS	DNH
water bed	Y	N	NS	DNH
hot tub	Y	N	NS	DNH
pool	Y	N	NS	DNH
aquarium	Y	N	NS	DNH
house plants	Y	N	NS	DNH
auto batteries	Y	N	NS	DNH
other ________________	Y	N	NS	DNH
______________________	Y	N	NS	DNH

5. **Does the quality of your water increase the work/chores around home? If so, circle (O) about how many extra hours per week you or others have to work because of poor water quality?**

WORK/CHORES	NONE	LESS THAN 1 HOUR	1 - 3 HOURS	MORE THAN 3 HOURS
Cleaning around home	0	< 1	1 - 3	≥ 3
Laundry	0	< 1	1 - 3	≥ 3
Operating/recharging water softener, replacing water filters	0	< 1	1 - 3	≥ 3
Dishes/food preparation	0	< 1	1 - 3	≥ 3

YOUR WATER USING APPLIANCES

6. **For each appliance listed below that you have in your home, indicate to the best of your knowledge how long (YEARS) it has been in your home (write n/a [not applicable] in years column (1) if you do not have the appliance). In column (2) indicate if it has been REPAIRED by writing in the YEAR. Then describe the latest repair in column (3) (what was done?), and its COST or circle CW if covered under warranty in column (4)?**

	(1) YEARS	(2) REPAIRED? Year?	(3) WHAT WAS REPAIR?	(4) COST ($) OR CW?
Example* *Dishwasher	*8*	*1989*	*Sprayer Arm Replaced*	*$65* CW
Water heater	______	____	____________________	_____ CW
Clothes washer	______	____	____________________	_____ CW
Dishwasher	______	____	____________________	_____ CW
Water softener	______	____	____________________	_____ CW
Other water treatment unit	______	____	____________________	_____ CW
Humidifier	______	____	____________________	_____ CW
Garbage Disposer	______	____	____________________	_____ CW
Evaporative (swamp) cooler	______	____	____________________	_____ CW

7. **For each appliance purchased in the last five years (1986 to now), indicate AGE OF OLD ONE in YEARS (that new one replaced) (write n/a [not applicable] in years column if you do not have the appliance), YEAR BOUGHT/OBTAINED REPLACEMENT/NEW one, and whether you PURCHASED A SERVICE CONTRACT? If yes, indicate its COST, length of time covered (YEARS), and number of REPAIRS DONE UNDER SERVICE CONTRACT.**

	AGE OF OLD ONE YEARS	YEAR BOUGHT OBTAINED/ REPLACE-MENT/NEW	PURCHASED A SERVICE CONTRACT? NO	YES	SERVICE CONTRACT COST FOR HOW MANY YEARS $	YRS.	REPAIRS DONE UNDER SERVICE CONTRACT HOW MANY?
Example *Clothes washer*	17	1987	N	Y	$176	3	0
Water heater	____	_____	N	Y	____	____	_____
Clothes washer	____	_____	N	Y	____	____	_____
Dishwasher	____	_____	N	Y	____	____	_____
Water softener	____	_____	N	Y	____	____	_____
Other water treatment unit	____	_____	N	Y	____	____	_____
Humidifier	____	_____	N	Y	____	____	_____
Garbage disposer	____	_____	N	Y	____	____	_____
Evaporative (swamp) cooler	____	_____	N	Y	____	____	_____

8. **For each fixture listed below indicate whether you have REPLACED it (WHEN?), age WHEN REPLACED (YEARS), replacement COST, and check (✓) by whom work replacement was DONE.**

	REPLACED? YES WHEN?	HOW OLD WHEN REPLACED? YEARS	COST $	DONE BY HOUSEHOLD MEMBER/ FRIEND	DONE BY PLUMBER/ CONTRACTOR
Example Shower head	1989	8	$ 45.	✓	____
Kitchen sink	____	____	$____	____	____
Kitchen sink faucet	____	____	$____	____	____
Bathtub	____	____	$____	____	____
Bathtub faucet/drain	____	____	$____	____	____
Shower head (tub)	____	____	$____	____	____
Lavatory/bathroom sink	____	____	$____	____	____
Lavatory sink faucet	____	____	$____	____	____
Shower stall	____	____	$____	____	____
Shower faucets/ showerhead	____	____	$____	____	____
Toilet (complete)	____	____	$____	____	____
Toilet flushing mechanism	____	____	$____	____	____

On the lines below indicate other replacements and information (as above) for other/ additional bathroom, laundry, faucets, fixtures, etc..

WHAT FIXTURE/ITEM?				
____________	____	____	$____	________
____________	____	____	$____	________
____________	____	____	$____	________

9. **Of what are the water pipes in or coming into your home made? Check (✓) all that are used.**

______PLASTIC ______COPPER ______IRON ______OTHER, write in _________

Have you replaced any hot or cold water pipes?
____ No
____ Yes, when (year) ______
How much did this cost? $______
What were the new pipes (check (✓))?
______PLASTIC _____COPPER ______IRON ______OTHER, write in _________

10. **Of what are the waste water (sewer) pipes made (check (✓))?**

______PLASTIC ______COPPER ______IRON ______OTHER, write in _________

Have you replaced any sewer pipes?
____ No
____ Yes, when (year) ______
How much did this cost? $______
What were the new pipes (check (✓))?
______PLASTIC ______COPPER ______IRON ______OTHER, write in _________

11. **Some people improve the water by treating it. Do you have any of these water conditioning units? On the left check (✓) the blanks of those you have and indicate monthly operating costs in blanks on right.**

	Monthly Cost
____water softener, own	$ ______
____water softener, rent/lease	$ ______
water filter	$ ______
____ whole house	$ ______
____ one faucet (as kitchen sink)	$ ______
____ other __________________	$ ______
____distiller	$ ______
____reverse osmosis system	$ ______
____other ___________________	$ ______
____none of the above	

LAUNDRY

12. **How many loads of wash are done at a laundromat in a week? Circle (◯) best response.**

0 1 - 2 3 - 5 6 - 8 9 OR MORE

13. **How many loads of wash are done in your home in a week? Circle (◯) best response.**

0 1 - 2 3 - 5 6 - 8 9 OR MORE

14. **In doing laundry, for normal size loads, do you usually use more, less, or the same amount of detergent as stated on the detergent box/bottle or washer instructions? Check (✓) your response.**

___ more, About how much more? **Circle (◯) amount-cup(s) per load** ¼ ½ ¾ 1 more than 1
___ less, About how much less? **Circle (◯) amount-cup(s) per load** ¼ ½ ¾ 1 more than 1
___ same

15. **What laundry products do you usually use? For each that you usually use circle (◯) whether you use powdered (P) or liquid (L).**

PRODUCT	USE? POWDERED	LIQUID
Detergent (no added ingredients)	P	L
Detergent with added bleach	P	L
Detergent with added softener	P	L
Detergent specifically for cold water	P	L
Bleach	P	L
Water softener	P	L

YOUR CAR/TRUCK

16. **Do you have a car/truck that has needed cooling system repair (radiator, heater core, water pump, overheating)?**

____ No, what is year of your most used vehicle? 19____
____ Yes, age of vehicle(s) when repair was done?
Vehicle 1; _______ years old (when repaired), $_______ cost of repair(s)
Vehicle 2; _______ years old (when repaired), $_______ cost of repair(s)
Vehicle 3; _______ years old (when repaired), $_______ cost of repair(s)

17. **What do you usually use in your car/truck radiator?**

____ 100% antifreeze
____ Antifreeze and bottled water
____ Antifreeze and tap water
____ Tap water
____ Have it done at a garage or shop so I am not sure

BOTTLED WATER

18. **People may purchase bottled water for certain uses. Do you use bottled water? Do not include sparkling or mineral waters as bottled water when answering.**

____ No, please **go to question 19**
____ Yes, How much do you spend per week for bottled water? $______ estimated weekly cost

Check (✓) all uses you make of bottled water.

____ drinking
____ making beverages (coffee, juices, etc.)
____ infant formula
____ cooking
____ other ______________________
____ ____________________________

How much bottled water do you use per week? Check (✓) the amount.

____ less than 2 gallons
____ 2 - 5 gallons
____ 6 - 10 gallons
____ 11 or more gallons

Why do you use bottled water? Check (✓) the most important reason.

____ taste/flavor
____ health (low sodium)
____ safety concerns
____ color/appearance
____ follow instructions/lessen damage to steam iron, batteries, etc.

19. **Because of the taste or quality of your tap water, does your household use <u>more</u> soft drinks, fruit juices, or other canned or bottled beverages to avoid drinking tap water?**

____ No
____ Yes $______ estimated added weekly cost for soft drinks, etc. bought to avoid tap water

VALUE OF IMPROVED WATER

All water contains some dissolved minerals. It picks up these minerals naturally as it travels over rocks and through soil. High mineral content of water may cause bad tasting water, shortened service lives of appliances and fixtures and other problems.

20. **Considering the quality of tap water in your home, should something be done to lower its mineral content? Check (✓) the response that best describes your opinion.**

____ No, mineral content is already low, **go to question 27**
____ Yes, **go to question 21**

21. Now, imagine that there is a plan to improve the water treatment and supply system to lower the mineral content of your local municipal water. Suppose that the improved water is to be of low mineral content so that scaling, staining, bad taste, and other problems caused by high mineral content no longer occur. Assume that the cost of the proposed project will be charged to all water users on their water bills.

Of the amounts listed below, in dollars *per month*, please circle (O) the amount closest to the maximum increase in your water bill you would accept and still favor the improvement project. If you are billed over some other period, remember that these figures are in dollars per month.

$0	$2	$4	$6	$8
$10	$12	$14	$16	$18
$20	$22	$24	$26	$28
$30	$32	$34	$36	$38
$40	$42	$44	$46	$48
$50	$52	$54	$56	$58

If you circled any amount from $2 to $56, please **go to question 24.**

If you circled $0, please **go to question 22**, if $58 **go to question 23.**

22. **As you circled $0 per month, this was because (please check (✓) best answer, or provide one of your own).**

____ I object to the idea of funding the project through water bills

____ I object to putting a dollar value on water quality.

____ Other reason, write in. ____

____

Now, go to question 27.

23. **As you circled $58 per month, this was because**

____

____

24. Some water-quality problems cost you money. These may include the costs of bottled water and the costs of more frequent appliance repairs and replacements. Other water-quality problems do not cost you money but may annoy you. These may include:

* having bad tasting water for drinking, for cooking and brushing teeth,

* having to take the time and trouble to purchase more bottled water, weekly,

* having to scrub fixtures more often.

How much, in dollars *per month* of the amount you circled in question 21, would you say is due to poor water quality that does not cost you money (but is a bother, annoyance, or more work)? Circle (O) amount.

$0	$2	$4	$6	$8
$10	$12	$14	$16	$18
$20	$22	$24	$26	$28
$30	$32	$34	$36	$38
$40	$42	$44	$46	$48
$50	$52	$54	$56	$58

If you circled any amount from $2 to $56, please **go to question 27.**

If you circled $0, please **go to question 25**, if $58 **go to 26.**

25. **As you circled $0 per month, this was because (please check (✓) best answer, or provide one of your own).**

____ I object to putting a dollar value on water quality.

____ I object to the idea of funding the project through water bills.

____ Other reason, write in. ____

____

Now, please go to **question 27.**

26. **As you circled $58 per month, this was because**

____

____

YOU, YOUR FAMILY, AND YOUR HOME

27. **Describe your housing and water system. First, check (✓) the characteristic that best describes your present housing unit. Then check (✓) the characteristic that describes your rent/own situation. Lastly, check (✓) your home's source of water.**

HOW MANY PERSONS LIVE IN YOUR HOME?

____ 1 ____ 4
____ 2 ____ 5
____ 3 ____ 6 or more

YOUR HOUSING UNIT?

____ Single family detached
____ Duplex/row house
____ Apartment
____ Mobile home
____ Other (specify) ____________________

YOUR RENT/OWN SITUATION?

____ Rent
____ Own
____ Other (specify) ____________________

YOUR WATER?

____ City/town system; Which water district? ________________
____ Subdivision well or system (not city/town)
____ Own well
____ Other (specify) ________________

28. **How many years have you lived in your present home?** __________ years

29. **To the best of your knowledge, about when was your home built? We mean <u>first</u> constructed, not when remodeled, added to, or converted. Check (✓) your choice.**

____ Before 1940
____ 1940 - 1949
____ 1950 - 1959
____ 1960 - 1969
____ 1970 - 1979
____ 1980 - 1984 (If known, please put year ________.)
____ 1985 or after (If known, please put year ________.)

30. **What is your current zip code?** _ _ _ _ _

In what year did you move to your current zip code? ___________ year.

What was your former zip code? _ _ _ _ _

31. **Your sex** _____ Female _____ Male

32. **What is your highest level of education (check (✓) one)?**

____ 8th grade or less
____ Grades 9 through 11
____ High school graduate or equivalent (GED)
____ Some college, technical, or trade school beyond high school (no degree)
____ Junior/community (2-year) college degree or certificate
____ College/university degree (bachelor's)
____ Graduate/professional degree

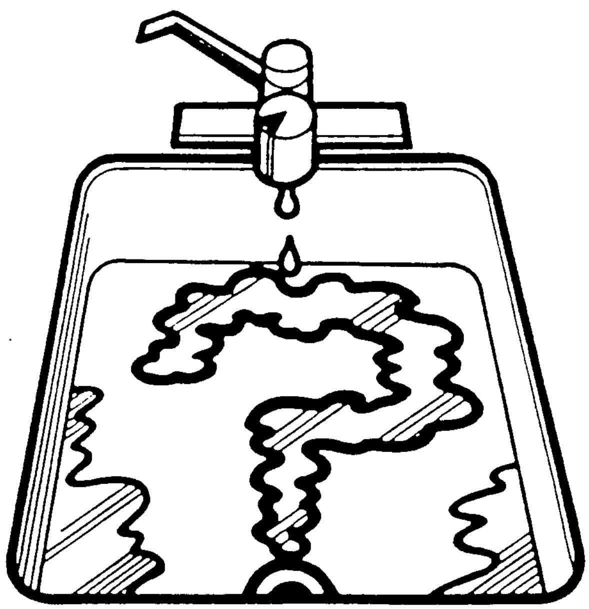
33. **Which category describes your 1990 total family income (before taxes)? Check (✓) the appropriate category.**

____ $19,999 or less	____ $35,000 to $49,999
____ $20,000 to $24,999	____ $50,000 to $64,999
____ $25,000 to $34,999	____ $65,000 or more

Is there anything we may have overlooked? Please use this space for any additional comments you would like to make about the water supply and its quality and use in your home and/or your community.

THANK YOU!

Water in Your Community: Appliances



☼ A STUDY OF EFFECTS OF MINERALS IN WATER ☼

☼ ALONG THE ARKANSAS RIVER ☼

Your help with this effort is greatly appreciated!
Please use the back page for comments or to add detail.
Thank you!

APPLIANCE REPAIR FIRMS

1. How long has your firm been doing business in the community where you are currently located?

_______ years

WATER IN YOUR COMMUNITY

2. How do you rate the general quality of your community's domestic water supply? Check (✓) your response.

_____ Excellent
_____ Good
_____ Fair
_____ Poor

3. In your opinion, how has the quality of your community's water changed in the last three years? Check (✓)your response.

_____ Improved
_____ No change
_____ Gotten worse

4. How would you describe the quality of your community's water as it relates to its effect on household piping, fixtures, and water-using appliances? To describe your water, place a check (✓) on one of the five lines of the scale for each effect.

Example						
Rusty	____	____	____	_✓_	____	*No Rust*

Corrosive	____	____	____	____	____	Not Corrosive
Leaves No Scale	____	____	____	____	____	Scale Forming
Stains Fixtures	____	____	____	____	____	Not Staining

5. Please estimate the percentage of homes in your customer base that use water from private wells for the indoor plumbing system.

_______ percent

Please respond to the following questions with regard to only those customers on the local municipal water supply.

APPLIANCE REPAIR HISTORIES

6. For each appliance listed, check the appropriate box to indicate the *most frequent* cause of repair of the appliance. Please check (✓) only <u>one box</u> per appliance (in each line across) or write in some other reason.

Appliance	Most Frequent Cause of Repair			
	Water Damage		Mechanical or Electrical	Other, Please Write in
	Corrosion	Scaling		
Dishwasher				
Clothes washer				
Water heater, gas				
Water heater, electric				
Garbage disposal				
Evaporative cooler				

7. For each appliance listed, estimate the <u>number</u> of service calls that would be expected during the service life of each appliance and estimate the <u>average cost</u>, parts plus labor, of a typical service call.

Appliance	Number of Calls Expected	Average Cost of One Call
Dishwasher	_______	$_______
Clothes washer	_______	$_______
Water heater, gas	_______	$_______
Water heater, electric	_______	$_______
Garbage disposal	_______	$_______
Evaporative cooler	_______	$_______

8. For each appliance listed, check the appropriate box to indicate the *most frequent* cause of replacement of the appliance. Please check (✓) only one box per appliance (in each line across) or write in some other reason.

Appliance	Most Frequent Cause of Replacement			
	Water Damage		Mechanical or Electrical	Other, Please Write in
	Corrosion	Scaling		
Dishwasher				
Clothes washer				
Water heater, gas				
Water heater, electric				
Garbage disposal				
Evaporative cooler				

9. On average, how old would you estimate the following water-using appliances to be at the time they are replaced?

Appliance	Average Age (years) When Replaced
Dishwasher	______
Clothes washer	______
Water heater[1], gas	______
Water heater[1], electric	______
Garbage disposal	______
Evaporative cooler	______

[1]Assume that sacrificial anodes are not replaced when spent.

10. Does your firm usually remove the sacrificial anodes from water heaters before the water heaters are put into service?

Yes______, please state the reason you do this:

____

____

No______, please estimate the useful life of the sacrificial anodes: _______ years

Do you find that replacing the anodes extends the service life of water heaters?

Yes______ No______.

What percentage of your customers replace or have someone else replace the sacrificial anodes?

Percent _________.

If anodes are replaced when spent, how long will water heaters typically last?

Gas: __________years.

Electric: __________years.

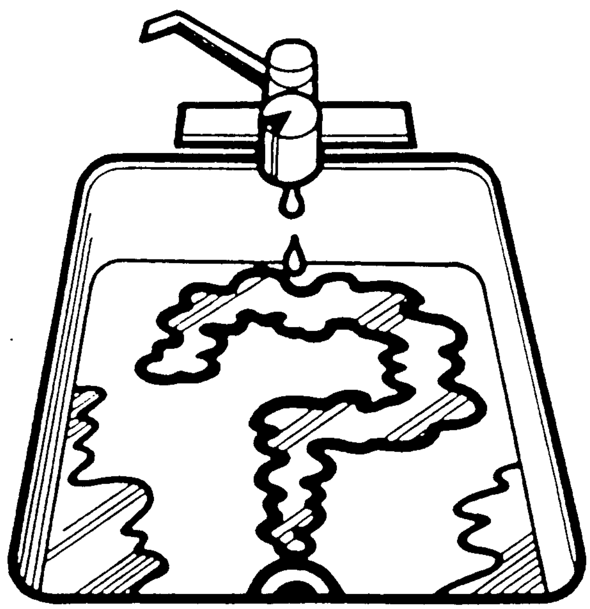
11. What is the average service life of a heating element for an electric water heater? __________ years.

What percentage of your customers have electric water heaters? ____________ percent.

Is there anything we may have overlooked? Please use this space for any additional comments you would like to make about the water supply and its quality and use in your community.

THANK YOU!

Water in Your Community: Residential Plumbing



☼ A STUDY OF WATER AND MINERAL CONTENT ☼

☼ THE ARKANSAS RIVER ☼

Your help with this effort is greatly appreciated!
Please use the back page for comments or to add detail.
Thank you!

PLUMBING CONTRACTORS

1.How long has your firm been doing business in the community where you are currently located?

_______ years

WATER IN YOUR COMMUNITY

2. How do you rate the general quality of your community's domestic water supply? Check (✓) your response.

_____ Excellent
_____ Good
_____ Fair
_____ Poor

3. In your opinion, how has the quality of your community's water changed in the last three years? Check (✓) your response.

_____ Improved
_____ No change
_____ Gotten worse

4. How would you describe the quality of your community's water as it relates to its effect on household piping, fixtures, and water-using appliances? To describe your water, place a check (✓) on one of the five lines of the scale for each effect.

Example

Rusty	___	___	___	✓	___	*No Rust*

Corrosive	___	___	___	___	___	Not Corrosive
Leaves No Scale	___	___	___	___	___	Scale Forming
Stains Fixtures	___	___	___	___	___	Not Staining

5. Please estimate the percentage of homes in your community that use water from private wells for the indoor plumbing system.

______ percent

Please respond to the following questions with regard to only those customers served on the local municipal water supply. *2*

POTABLE WATER PIPING

6. What is your firm's experience in replacing household water piping?

On average, how old are the piping systems you replace for each type of pipe (in column (1) write in number of years)? On average, how much does a more-or-less complete household replacement job cost (parts plus labor) for each type of pipe (write in the dollar amount in Column (2)? If your firm has never replaced pipes of a given type, please write in NA (column (1)).

Type of Pipe (water)	Average (typical) Age (years) at Time of Replacement (1)	Average Cost for Almost Total Replacement (2)
Galvanized steel	________	$________
Copper	________	$________
Plastic	________	$________
Other, write in ____________	________	$________

7. What is your firm's experience in repairing and partially replacing household water piping?

During the typical service life of a piping system, how many times would you expect repairs to be required for each type of pipe (write in the number in column (1))? On average, how much would each repair job cost (write in the dollar amount in column (2))?

Type of Pipe (water)	Number of Repairs Expected (1)	Average Repair Cost (2)
Galvanized steel	________	$________
Copper	________	$________
Plastic	________	$________
Other, write in ____________	________	$________

3

8. When your firm replaces water pipe, in what percentage of homes (column (1)) do you install each type of pipe? Estimate the percentage of homes (column (2)) in your municipal customer base having mostly each type of pipe.

Type of Pipe (water)	When Replacing, Percentage of Jobs Using this Type (1)	Percentage of Homes Having Mostly this Type (2)
Galzvanized steel	____%	____%
Copper	____%	____%
Plastic	____%	____%
Other, write in ______________	____%	____%

WASTEWATER PIPING

9. What is your firm's experience in replacing household wastewater pipes?

On average, how old are the pipes you replace for each type of pipe (write in the number of years in column (1))? On average, how much does a more-or-less complete household replacement job cost for each type of pipe (write in dollar amount in column (2))? If your firm has never replaced a given type of pipe, please write in NA (column (1)).

Type of Pipe (wastewater)	Age (years) at Time of Replacement (1)	Average Cost for Complete Replacement (2)
Galvanized steel	________	$________
Copper	________	$________
Plastic	________	$________
Cast iron	________	$________
Other, write in ______________	________	$________
Other, write in ______________	________	$________

10. What is your firm's experience in repairing and partially replacing household wastewater pipes?

During the typical service life of a piping system, how many times would you expect repairs to be required for each type of pipe (write in the number in column (1))? On average, how much would each repair job cost (write in the dollar amount in column (2))?

Type of Pipe (wastewater)	Number of Repairs Expected (1)	Average Cost for Repair Job (2)
Galvanized steel	________	$________
Copper	________	$________
Plastic	________	$________
Cast iron	________	$________
Other, write in ______________	________	$________
Other, write in ______________	________	$________

11. When your firm replaces wastewater pipes, in what percentage of homes (column (1)) do you install each type of pipe as a replacement? Estimate the percentage of homes in your municipal customer base having (mostly) each type of pipe (write in the percentage in column (2)).

Type of Pipe (wastewater)	When Replacing, Percentage of Jobs Using this Type (1)	Percentage of Homes Having this Type (2)
Galvanized steel	_____%	_____%
Copper	_____%	_____%
Plastic	_____%	_____%
Cast iron	_____%	_____%
Other, write in ______________	_____%	_____%
Other, write in ______________	_____%	_____%

5

FIXTURES AND APPLIANCES

12. On average, <u>how old</u> would you estimate the following fixtures and appliances to be at the time they are replaced in most homes?

Fixture	Type	Average Age (years) When Replaced
Kitchen sink	Enameled metal	_______
Kitchen sink	Stainless steel	_______
Kitchen faucet	Brass or copper	_______
Kitchen faucet	Plastic	_______
Shower stall	Plastic	_______
Toilet		_______
Toilet flushing mechanism		_______
Sink (lavatory) faucet	Brass or Copper	_______
Sink (lavatory) faucet	Plastic	_______
Shower head	Brass or copper	_______
Shower head	Plastic	_______
Shower or bath faucet	Brass or copper	_______
Shower or bath faucet	Plastic	_______
Water heater[1]	Gas fired	_______
Water heater[1]	Electric	_______
Lawn sprinkler system		_______

[1]Assume that sacrificial anodes are not replaced when spent.

Add other water-using fixtures that you usually repair/replace. Write in the same information as above.

Other ________________ ________________ _______

Other ________________ ________________ _______

Other ________________ ________________ _______

Other ________________ ________________ _______

13. Does your firm usually remove the sacrificial anodes from water heaters before the water heater is put into service?

______Yes, please state the reason for doing so:

____

____

____

____

______No, please estimate the useful life of the sacrificial anodes: _________ years

Do you find that replacing the anodes extends the service life of water heaters?
Yes______ No______

What percentage of your customers replace or have someone replace the sacrificial anodes? _________ percent.

If anodes are replaced when spent, how long will water heaters typically last?
Gas_________ years
Electric__________ years.

14. What is the average service life of a heating element for an electric water heater?
__________ years.

What percentage of your municipal customers have electric water heaters?
_____________ percent.

Is there anything we may have overlooked? Please use the back cover for any additional comments you would like to make about the water supply and its quality in your community.

THANK YOU!