HALOPHYTE CROPS AND A SAND-BED SOLAR CONCENTRATOR TO REDUCE AND RECYCLE INDUSTRIAL, DESALINATION AND AGRICULTURAL BRINES

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Desalination Research and Development Program Report No. 35

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GLOSSARY

E.C.	Electrical conductivity
F	F-ratio
LF	Leaching fraction
LSD	Least significant difference
P	Probability level
SAR	Sodium absorption ratio
S.E.	Standard error
n	Sample size
ppm	Parts per million (weight to weight)
ppt	Parts per thousand (weight to weight)
S	Sorptivity
E/D_I	Evaporated fraction (evaporation divided by irrigation)
NaCl	Sodium chloride (halite)
$CaCO_3$	Calcium carbonate
$CaSO_4 \cdot 2H_20$	Calcium carbonate dihydrate

SI Metric Conversions

From	To	Multiply by
ft	m	3.048 000 E - 01
in	m	2.540 000 E - 02
ft^2	m^2	9.290 304 E - 02
kgal	m^3	3.785 412
Mgal	m^3	3.785 412 E + 3
acre-ft	m^3	1.233 489 E + 3
lb/in^2	kpa	6.894 757
lb/in^2	BAR	6.894 757 E - 02
°F	°C	$t°_C = (t°_F - 32)/1.8$

1. EXECUTIVE SUMMARY

Handling of saline wastewater generated from industrial and agricultural activities is an increasing concern in the western states. This study was undertaken to explore ways to reduce brine or concentrate volumes using halophytes then a sand bed prior to the final processing either though containments or salt production. In the first part of the study, a halophyte shrub (*A. nummularia*) and two salt-tolerant grasses (*Paspalum vaginatum* and *Paspalum distichum*) were irrigated with well water and cooling tower blowdown water for 4 years at a power plant in Tempe, Arizona. Plants were grown in open plots (the results reported here) and lysimeters (previously reported) and results were used to assess the feasibility of using halophytes for the disposal of industrial brines. The results showed that *A. nummularia* can be irrigated indefinitely with 2.1-2.8 m/yr (6.8-9.1 ft/yr) of water of salinity up to 4100 ppm under low leaching fraction (<10%) without reaching the threshold soil salinity for yield reduction. This crop is recommended for recycling brine, because it combines high water use with high salt tolerance. On the other hand, *Paspalum* spp. had lower water use and salt tolerance than *A. nummularia* and are not recommended as the sole crops for brine reuse. They could be used in a mixed planting with halophyte shrubs, however. At this site, soil moisture and salinity did not build up to levels of concern over 4 years, despite the presence of an impeding layer at 3.5-5 m (11.3-17 ft) and the high irrigation rates employed. We conclude that irrigation of halophytes is a suitable disposal method for industrial brines wherever local soils and land use practices are compatible with this option. An evapotranspiration model for scheduling *A. nummularia* irrigation based on atmospheric water demand was validated, allowing the results to be transferred to other locations.

In the second part of the study methods to further reduce the volume of concentrate by evaporation on a sand bed were explored. Two separate experiments were conducted in a greenhouse. The first experiment was conducted with the objective of developing guidelines for selecting bed materials and profile configurations. Results indicated that fine, medium or coarse sand, as well as loamy sand and mortar sand, provided good water infiltration, adequate water holding capacity and excellent water evaporation characteristics, and could be used as the primary bed materials. By contrast, very coarse sand did not evaporate water as well as the other materials. In the second part of the study, the objective was to evaluate the extent of saline water volume reductions that can be achieved without causing a major reduction in water infiltration, drainage and evaporation over time. The bed materials tested were mortar sand and loamy sand with bed thicknesses of 5 and 10.5 cm (2 and 4.1 inches). Sodium chloride (NaCl) solutions were tested at concentrations of 20, 40, 60 and 80 ppt [parts per thousand (weight-to-weight)]. Results indicated that salt accumulation had a relatively small impact on infiltration rates but did cause drainage problems when 60 and 80 ppt solutions were applied at 10% leaching fraction. Salt accumulation in beds irrigated with those two concentrations also impeded evaporation, especially on loamy sand. These observations suggest that sand beds consisting of about a 5 cm (2 inch) layer of mortar sand or coarse sand over a thin layer of gravel are potentially suitable for reducing saline wastewater containing 40 ppt and possibly up to 60 ppt of dissolved solids. The system can be operated with a leaching fraction of 10-20% which yields a volume reduction of 80-90%. Sand beds may prove to be useful as a way to provide brine for solar ponds as well as a replacement for evaporation ponds, possibly in conjunction with the development of auxiliary salt disposal pits.

2. SECTION I: INTRODUCTION

Overview of the Brine Disposal Problem. Large volumes of brines are generated by irrigated agriculture (Westcot, 1988), electric generating facilities (Engel et al., 1985; Glenn et al., 1998b) and the desalination industry (Riley et al., 1997). Disposing of these brines has become a serious problem in many locations in the western United States. Typically, brines are diluted into large water bodies such as rivers, lakes or the ocean, but many western locations lack such receiving bodies. Other disposal options have become untenable due to environmental concerns. For example, brines have been placed in evaporation ponds throughout the west, but as the brines concentrate, trace elements such as selenium, boron and heavy metals can accumulate to hazardous levels (Ong et al., 1995). These ponds often support an active biological food chain, which further concentrates toxic elements in fish and invertebrates, which can then poison waterfowl which feed in the ponds (Hothem and Ohlendorf, 1989).

Brines are often discharged into irrigation canals or municipal sewer systems, where they are diluted with low-salinity water (Westcot, 1988), but these disposal methods simply displace the salinity problem away from the site of production, and downstream water users are increasingly reluctant to accept brines even after dilution. Further, water disposed to sewage treatment plants must meet drinking water standards with respect to toxic element concentrations, and brines often exceed these limits. It is possible to reduce brines to dryness in forced draft evaporators or solar ponds under controlled conditions (Hays and Kipps, 1992). These methods are environmentally safe but are too costly to handle the large quantities of dilute brine generated by irrigation districts, desalination plants and power producers.

As examples of the seriousness of the brine disposal problem, agricultural brines have been responsible for wildlife poisoning in the San Joaquin Irrigation District in California (Presser, 1994), while the nation's largest brine repository, the Salton Sea, is now plagued by bird and fish kills attributed in part to increasing salinity (Boyle, 1996). Salinity in the Amistad International Reservoir, which supplies drinking water to El Paso and Juarez, has increased due to discharge of agricultural drainage water into the middle Rio Grande and Pecos River, and will soon exceed the state drinking water standard of 1 ppt TDS (total dissolved solids) if the saline drainage streams are not controlled (Miyamoto and Mueller, 1994). Operation of the Yuma Desalting Plant has been delayed in part due to questions about concentrate disposal in Mexico; and in Tucson, one of the impediments to installing a desalting plant to treat the municipal water supply is the question of how to dispose of the concentrate (Riley et al., 1997). Clearly, environmentally safe yet low cost methods for concentrate and brine disposals are needed in arid environments.

The best solution to the brine disposal problem may be to reuse the water for crop production or other beneficial, consumptive uses near the site of production (Rhoades et al, 1989). Irrigating with highly saline water, if not managed correctly, can be hazardous to soils and aquifers. However, this approach has the advantage of keeping the salinity problem localized, and if practiced correctly it results in storage of salt in the vadose zone above aquifers but below the root zone, where salt is least likely to cause environmental damage. Reuse of saline water for irrigation has been endorsed by the USDA Salinity Lab (Rhoades et al., 1989), the California Department of Agriculture (Karajeh et al., 1994) and other groups. In Arizona, the use of brines to irrigate crops or landscape plants is considered a beneficial use of industrial wastewater so long as best management practices with respect to irrigation methods are followed.

A fundamental problem with the reuse option is the low salt tolerance of most conventional crop and landscape plants (Ayars et al., 1993). Our research tested the feasibility of irrigating halophytes and other salt-tolerant plants with cooling tower brine from electric power plants. These brines generally range in salinity from 2 - 10 ppt TDS, similar to the range found in agricultural brines and desalination plant concentrate. Our hypothesis was that halophyte crops can greatly reduce the volume of brines through evapotranspiration of the bulk water, while producing useful products. In areas with deep water tables, irrigation of halophytes with brine is an acceptable disposal method by itself (Riley et al., 1997). In areas with perched water tables it may be necessary to recover the concentrated, subsurface drainage from below the halophyte field for evaporation to dryness (Karajeh et al., 1994). Since evaporating such water in open ponds can attract and poison wildlife, we tested the feasibility of a sand-bed evaporator to further reduce the volume of concentrated brine without the need for an exposed water surface. These results are reported later in Section II.

Halophyte Crops to Receive Brines. Halophytes are wild, salt-tolerant plants that grow in the world's salt marshes and salt deserts. Although they represent less than 2% of higher plant species, there is wide diversity of halophyte types, including grasses, forbs, shrubs and trees (Glenn, 1995). In the past 20 years, a number of species have been investigated as plants for livestock forage, oilseed production and soil stabilization in saline environments. Halophytes have been successfully irrigated with saline water sources, ranging in salinity from brackish cooling tower brine (1-4 ppt TDS)(Glenn et al., 1998b) up to hypersaline seawater (>40 ppt TDS)(Glenn et al., 1998a). Agronomic techniques suitable for halophytes grown across this salinity spectrum are under development (Miyamoto et al., 1996), but irrigated halophytes are still regarded as experimental crops and have not been implemented on a large scale, to our knowledge.

We analyzed four years of data in which a halophyte shrub and two salt-tolerant grasses were irrigated with cooling tower brine and well water at a western power plant. The management objective over the experiment was to maximize consumptive water use by halophytes, while minimizing leaching fraction (water discharged past the root zone). We present results on water use, soil moisture, soil chemistry, leaching fraction and conclusions regarding the safety and sustainability of this disposal method, based on the results.

3. CONCLUSIONS AND RECOMMENDATIONS

- *A. nummularia* irrigation requirement was 2.07 m/yr (6.7 ft/yr) over 4 years in open plot trials, irrigated with a mixture of well water and power plant blowdown water. Water use up to 2.8 m/yr (9.1 ft/yr) was obtained in lysimeter trials.

- *Paspalum spp.* required 1.60 m/yr (5.18 ft/yr) over the same period.

- Leaching fractions for *A. nummularia* and *Paspalum spp.* were low, 6.0-6.3%.

- At equilibrium conditions, the soil sodium content of plots irrigated with 4100 ppm blowdown water under 6.0-6.3% leaching fraction is projected to remain below the threshold level for yield reduction for *A. nummularia* but will exceed the threshold level for *Paspalum spp.*

- Despite the presence of an impeding layer at 3.5-5 m (11.3-16.2 ft) soil depth in these plots and the use of high irrigation rates, soil profiles remained below saturation and did not increase in soil moisture content over 4 irrigation seasons.

- The evapotranspiration model developed for scheduling irrigation of *A. nummularia* in previous lysimeter trials was validated by these open plot trials.

- *A. nummularia* has the desired attributes of a crop to recycle brine: high consumptive water use to maximize uptake; high salt tolerance to minimize the required leaching fraction; and high biomass yield of a useful forage. It is recommended as a crop to recycle brines.

- *Paspalum* grasses have moderate water use and salt tolerance. They are not recommended as the sole crops to recycle blowdown but they can be part of a mixed planting with *Atriplex* shrubs.

- Disposal of brines through the production of halophyte crops can be recommended wherever local soil and land use practices permit.

4. WORK PERFORMED

4.1 Methodology

The work was performed at Arizona Public Services' Ocotillo Power Plant in Tempe, Arizona from April, 1994 to October, 1998. The power plant was formerly a cotton farm on a terrace in the flood plain of the Salt River. Halophytes were grown in 12, individually irrigated, 88 m^2 (924 ft^2) plots (see plot layout, Figure 4-1). The plots were located at two, 528 m^2 (5,542 ft^2) sites approximately 10 m (32.4 ft) apart on the power plant property, each site containing 6 adjacent plots. Two plots each of *Atriplex nummularia* (oldman saltbush), *Paspalum vaginatum* (seashore paspalum) and *Paspalum distichum* (ditch paspalum) were grown at each site in a randomized design. The predominant soil types were sand and silty sand (Typic Torrefluvent) over a gravel-and-cobble layer at 3.5-5 m (11.3-16.2 ft) depth and with a 0.1-0.2 m (0.3-0.6 ft) clay lens at 2.0-2.5 m (6.5-8.1 ft) depth (Geosystems Analysis, Inc., 1997). The cobble layer was encountered at shallower depth in Site 2 than in Site 1. Mean bulk density of soil samples from cores was 1.55 (S.E. = .04, n = 6), volumetric water content at saturation was 0.426 cm^3/cm^3 (S.E. = 0.02), porosity was 0.416 cm^3/cm^3 (S.E. = 0.01) and saturated hydraulic conductivity ranged from 4.5 x 10^{-3} cm/sec (1.45 x 10^{-4} ft/sec) for sand layers to 1 x 10^{-7} cm/sec 3.24 x 10^{-9} ft/sec) for clay layers (Geosystems Analysis, Inc., 1997).

Each plot had an access port in the center of the plot, drilled to a depth of 3-5 m (9.7-16.2 ft), through which soil moisture was measured using a neutron hydroprobe. The depth of the access port was determined by the depth at which the cobble was reached, since the auger would not penetrate beyond this layer. Four additional hydroprobe ports (controls) were located 3 m (9.72 ft) outside each set of plots, to monitor soil conditions in the absence of irrigation. Two plots of each plant type were grown at each site. Each week, soil moisture was determined at depths of 0.3, 0.6, 0.9, 1.5, 3.0 and 4.0-5.0 m (1, 2, 3, 5 and 10 ft)(depending on depth of the hydroprobe port) in each plot and for control locations. During the first 3 growing seasons (1995-1997), weekly irrigation volumes were scheduled to replace the moisture deficit in the top 0.6 m (2 ft) of soil profile in the grass plots and 0.9 m (3 ft) in the Atriplex plots, using methods in Glenn et al. (1998b). During the last growing season (1998), two methods were used to set irrigation schedules for *A. nummularia*: 1) the moisture deficit method and 2) calculation of monthly irrigation demand based on an evapotranspiration model, using crop coefficients developed in lysimeter studies (Glenn et al., 1998b). The irrigation formula for monthly water demand (cm/month) was: $y = 5.52x-56.2$, where x is atmospheric water demand in cm/month calculated from mean monthly temperature and photoperiod using the Blaney-Criddle method (American Society of Civil Engineers, 1973). One *A. nummularia* plot per site was irrigated by each method.

The irrigation source was mainly well water (ca. 500 ppm TDS) supplemented by power plant cooling tower blowdown (ca. 4200 ppm TDS) when it was available. The mean salinity of irrigation water over the study was 859 ppm (S.E. = 52, n = 150) obtaining 225 ppm sodium (see Glenn et al., 1998b, for further analyses). Plots were enclosed in 10 cm (0.3 ft), earth berms and water was distributed to plots by gravity. Plots were flooded to a depth of 5 cm (0.16 ft) or greater weekly. If the required irrigation volume calculated for a plot was less than this amount, water was not applied, but the irrigation requirement was added to the subsequent week's requirement. Generally, plots required weekly irrigation during May - October, but required irrigation only once every 4 weeks during December-February. At the beginning of the experiment when neutron probe ports were installed and again at the end of the 1998 irrigation season, soil cores for chemical analysis were taken from selected plots, representing Atriplex, Paspalum and Control locations at each site. Biomass production in *A. nummularia* plots was determined by harvesting one, 1 m^2 (10.5 ft^2) quadrant in each plot during the annual clipping of plants in October-December each year. Grass plots were mowed periodically and clippings were not recovered, so biomass production could not be estimated. Percent soil moisture content was determined from hydroprobe values using a calibration curve relating probe readings to gravimetric moisture content of site soil (Glenn et al., 1998b); volumetric soil moisture was calculated by assuming a uniform bulk soil density of 1.55 g/cm^3.

4.2 Results

Water Use by Halophytes. Water use ranged from 1.5-2.5 m/yr (4.9-8.1 ft/yr) among plots and (Table 4-1) and differed significantly ($P<0.05$) by plant type (*A. nummularia* > *P. distichum* and *P. vaginatum*) and site (Site 1 > Site 2). *A. nummularia* increased in water use each year while the grasses remained relatively constant in water use. Mean water use over years and sites was 2.07 m (6.71 ft) for *A. nummularia* and 1.60 m (5.18 ft) for the grasses. Site 1, which had a deeper soil profile than Site 2, required approximately 10% more irrigation water than Site 2. In 1998, *A. nummularia* irrigated according to the evapotranspiration model used 2.62 m (8.49 ft) of water compared to 2.28 m (7.39 ft) for plants irrigated by moisture demand in the top 0.9 m (2.92 ft) of soil (significantly different at $P<0.05$).

Soil Moisture Profiles. Soil moisture profiles are illustrated for four control plots (2 each from Sites 1 and 2), two *A. nummularia plots* (one each from Sites 1 and 2), and two grass plots (1 each from Sites 1 and 2)(Figures 4-2 - 4-9), from which soil cores were also taken for chemical analyses. Gravimetric soil moisture at field capacity (i.e., moisture in the top 1 m, 24 hours after irrigation) was ca. 12-14% and saturation (moisture content immediately after an irrigation) was >20%. Sites 1 and 2 plots differed in moisture distribution. Site 2 tended to have nearly-saturated soil at the bottom of the profile (over the cobble layer) where Site 1 was relatively dry (3-5% moisture) at the bottom. Saturated soil above the cobble layer suggested that this layer impeded water penetration to deeper soil layers. In all plots, moisture content tended to decrease rapidly from the surface to 1 m (3.2 ft), due to uptake by plants or evaporation from the soil, then increase at intermediate soil depths (above the clay layer). The driest part of the profile was the zone immediately below the clay layer but above the cobble layer. The soil profile of irrigated plots remained below field capacity throughout the experiment despite high irrigation volumes.

Trends in volumetric soil moisture over time were investigated by plotting mean monthly levels averaged over all soil depths (Figures 4-10 - 4-17). Moisture content increased in some plots (e.g. *A. nummularia* at Site 1, which was relatively dry at the start of the experiment) but remained constant or decreased in others (especially the control ports). Plots tended to contain the most water in September, at the end of the irrigation season. When September soil moisture levels were analyzed by year, the only significant time effect was that *A. nummularia* plots were drier in 1997 than other years; otherwise, soil moisture levels were remarkably stable among years (Table 4-2).

We tested the ability of plants to utilize excess water in the soil profile by withholding irrigation for one month at the end of the 1998 season (Table 4-3) (these measurements will be continued). *A. nummularia* lowered water content to the 3.1 m (10 ft) depth whereas the grasses only lowered water content to 1.5 m (5 ft) soil depth, reflecting different rooting depths. On average, the plants were able to decrease soil moisture content by 20% in just one month. We also analyzed soil moisture levels in *A. nummularia* plots irrigated by the evapotranspiration formula compared to soil moisture demand in the top 0.9 m (3 ft). Despite higher water application rates, the plots irrigated by the evapotranspiration formula did not have significantly ($P>0.05$) higher soil moisture levels in the soil profile at the end of the irrigation season.

Soil Chemical Profiles. Electrical conductivity, pH and cation content were measured in samples taken from cores through the soil profile of plots at the end of 1998 (Figures 4-18 - 4-25). Multipliers were used for different chemical parameters so that all constituents could be displayed on the same graph. In general, the concentration of chemical constituents did not vary markedly by soil depth. Cation content and E.C. of irrigated plots was actually lower than in control plots. Sodium was used to assess the effect of irrigation on soil salinity, since sodium is considered to be the cation responsible for growth reduction at high solenoids. Soil sodium content in irrigated plots did not vary significantly ($P>0.05$) by plant type or soil depth, but mean values across soil depths and plant types increased substantially ($P<0.001$), from 87.7 ppm at the beginning of the experiment (April, 1995) to 405.3 ppm at the end (September, 1998). E.C. of 1:1 soil extracts also increased significantly ($P<0.05$) in irrigated plots over the experiment.

Leaching Fractions. We were not able to directly quantify the volume of water discharged past the root zone (or cobble layer), but at equilibrium it can be estimated by the increase in salinity of the drainage water compared to the irrigation water: Leaching Fraction (LF) = Irrigation salinity/drainage salinity. The irrigated plots received 15-20 pore volumes of water over 4 years and did not exhibit significant gradients in salt content by soil depth at the end of the experiment, hence we assumed that equilibrium conditions were approached. We used mean values of soil moisture and sodium content at the end of the experiment to estimate leaching fractions for *A. nummularia* (2 plots) and *Paspalum spp.* (2 plots)(Table 4-4). Since the present experiment was conducted with a mixture of blowdown water and well water, we also projected, from the calculated leaching fraction, the mean soil sodium content that would be expected if each irrigation sources were used separately (Table 4-4).

Biomass Production. The primary purpose of the grass plantings was to serve as a turf, hence biomass production was not quantified. *A. nummularia* plots were cut back to approximately 60-70 cm height once a year during the study, producing a mean yield of 1.49 kg/m^2/yr (0.31 lb/ft^2/yr)(S.E. = 0.43, n = 4). Yields increased from 0.87 kg/m^2 (0.18 lb/ft^2) in 1996 to 1.98 kg/m^2 (0.41 lb/ft^2) in 1998 as the stands matured. The understory accumulated approximately 1.78 kg/m^2 (0.37 lb/ft^2) of standing biomass over the study whereas 0.33 kg/m^2 (0.07 lb/ft^2) dry weight of litter accumulated on the soil surface.

4.3 Discussion

The goals of this study were to determine if cooling tower blowdown could be effectively utilized for halophyte production at this site, and to generalize the results to other potential locations. We used the 4 years of open-plot data reported here as well as data from an overlapping set of experiments conducted in buried lysimeter basins at the site (Glenn et al., 1998b) to quantify irrigation demand and effects of irrigation on the soil. At the start of the experiment it was not known whether the cobble layer at 3.5-5 m (11-16 ft) would block water penetration and lead to an unacceptable accumulation of water and salt in the root zone. If that was the case, the soil profile could accumulate water and salt and become unusable for crop production over a relatively short period of time. Although some plots showed a tendency to accumulate water over time, overall the irrigated plots maintained constant water content from year to year, and their soil profiles were below saturation after 4 years. Further, the plants were able to reabsorb water from the profile at a rapid rate when irrigation was withheld. Hence, water accumulation in the root zone should not become a problem at this site.

Unlike water, salt is not lost by evapotranspiration and only a small fraction of the salt presented in the water supply is extracted by the plant tissues. Hence, removal of salt requires downward leaching. Based on soil sodium levels, we calculated that a leaching fraction of 6.0-6.3% was applied to plots. These are similar to the rates of 4-10% achieved in the lsyimeter experiments (Glenn et al., 1998b). Salt contents remained low in the soil cores, but this was because low-salinity water was used as the irrigation source. We project that soil salt levels will reach 2157 ppm sodium content at equilibrium when irrigated with blowdown water (4100 ppm TDS) (Table 4-4). *A. nummularia* irrigated with cooling tower blowdown water over 3 years in the lysimeter study reached a soil sodium content of 2108 ppm at the 90 cm (3 ft) depth by the end of the experiment, very similar to the projected equilibrium value from the present experiment.

At this soil sodium level, *A. nummularia* exhibited no reduction in yield or water use compared to plants grown at lower salinity (Glenn et al., 1998b). On the other hand, *Paspalum vaginatum* grown in lysimeters on blowdown water did suffer yield reduction at the end of 3 years (Glenn et al., unpublished data) and may not be suitable for long-term irrigation with blowdown water at a low leaching fraction. However, grasses could be used in mixed plantings with *A. nummularia* if the turf is over-irrigated to control salts in the root zone, and if *Atriplex* shrubs are interspersed in the turf planting to intercept water passing below the grass root zone. The spacing of plants for this scenario needs to be determined, since each plant type was grown in separate plots in the present experiment.

Mean annual water use by *A. nummularia* was 26% lower in the present experiment than in the previous lysimeter trials, because we calculated irrigation volume to replace moisture in only the top 0.9 m (3 ft) in the plots compared to 1.5 m (5 ft) in the lysimeters, to minimize discharge past the root zone. In the 1998 season, however, we found that plants could utilize 2.6 m/yr (8.4 ft/yr), determined by the evapotranspiration formula developed in the lysimeter study (Glenn et al., 1998b), without accumulating excess water in the soil profile. Hence, the formula method can be used to irrigate *A. nummularia*, which will eliminate the need for constant soil moisture monitoring to calculate irrigation demand (some monitoring will still be needed). Validation of the formula method also allows the results to be applied to other sites, basing irrigation on local meteorological data. By either method of calculating irrigation requirement, *A. nummularia* consumptive water use was equal to or higher than alfalfa and other high-water-use crops in Arizona (Wade et al., 1994).

At least two other factors need to be considered in deciding whether a site is suitable for halophyte cultivation. The first is the effect of high-sodium water on soil permeability. Neither this 4-year nor the previous 3-year experiment indicated that soil permeability might become a problem at this site, which contains sandy soils. SAR values in soil extracts ranged from 5-14, but the electrolyte content of all the irrigation supplies tested was sufficiently high that reduced permeability even of susceptible soils would not be expected. An additional factor to consider is discharge of leaching water and the salt it contains to deeper aquifers. While the discharge volume is relatively low, due to the low leaching fraction, the salt content of this water will be correspondingly high. Leachate water from lysimeters irrigated with cooling tower blowdown reached 39,201 ppm by the end of the third year of irrigation, and the equilibrium formula predicts that leachate from *A. nummularia* will be 68,332 ppm at a 6% leaching fraction.

This water may eventually reach the underlying aquifer, or it may remain in the vadose zone for decades or even hundreds of years, depending on the depth of the aquifer and the nature of the overlying soil layers (Riley et al., 1997). This is not just a consideration with halophyte irrigation, as conventional agricultural farms and urban landscapes also discharge salts to the aquifer. Conventional fields generally have only 40-50% irrigation efficiency, so they discharge larger volumes of water than halophytes, but at lower salinities. Aquifers under many irrigation districts are already saline from past discharge, and introducing halophytes into these districts is not considered hazardous (Westcot, 1988; Rhoades et al., 1989). At other sites, for example in the Imperial and San Joaquin Irrigation Districts in California, the fields have developed perched, saline water tables which are controlled through subsurface drains. Recycling the drain water on crops is used to reduce the volume through evapotranspiration before ultimate disposal to evaporation ponds (Karajeh et al., 1994). *A. nummularia* appears to be an ideal crop to accomplish this goal as it combines high consumptive use with low leaching requirement, and it produces a useful forage crop (Glenn et al., 1998b). The decision on whether to reuse brine for irrigation will always be site specific, and will depend on the nature of the soils and underlying aquifer, land use practices and what other disposal options are available (Riley et al., 1997). We believe the present results justify the choice of halophyte crops as part of an overall disposal strategy for brines in many locations in the western United States.

5. SECTION II: INTRODUCTION

Evaporation ponds have been commonly used to concentrate saline wastewater. The pond evaporation method is relatively easy to operate, and is fairly cost-effective. However, repeated incidents of bird-kills made it difficult to use as a sustainable system of saline wastewater disposal. Deep-well injection has also been used, but its use is highly site-specific, and is usually costly. An alternative method of disposing saline wastewater is to reuse it for growing salt-tolerant crops or landscaping plants, some of which fall into the category of halophytes. This method works well for a salinity range of 1000 to as high as 12,000 mg L^{-1} (Figure 5-1), provided that the site is free from usable aquifer, or from contamination of adjacent water resources. Detailed discussion of such an approach is given in Section I.

Saline wastewater with salinities too high for reuse or that contain substances toxic to wildlife can be evaporated by the use of brine evaporators or sand bed evaporators (e.g., Hayes and Kipps, 1992; Otani et al., 1998). Both of these methods are designed to evaporate saline water to form salts, principally halite (NaCl) and other evaporites. An alternative is to use chemical additives such as acetone to enhance salt precipitation and recovery. None of those methods is currently used extensively, partly because the salts harvested have little market value, and they are not conducive to large volume disposal.

The method to be explored in this project is a large scale sand-bed concentrator for reducing the volume of saline wastewater prior to feeding it to brine evaporators, sand-bed evaporators, or the final processing involving either saline solar ponds or salt burial pits. The principal aim is to concentrate large volumes of saline wastewater without ponding, then to send it off to the next processing in liquid form for the convenience of handling. Water application to a sand-bed concentrator is assumed to be made with a spray system similar to the one used recently for seawater irrigation trials. At present, however, little is known about the design and operation of such a system. The following studies were conducted I) for determining sand grain sizes and profile configurations suitable for concentrating saline water, and ii) for testing the performance of bench-scale sand beds for concentrating saline solutions. The work performed is largely exploratory, and a prototype sand bed concentrator is suggested for further testing and development.

6. CONCLUSIONS AND RECOMMENDATIONS

Findings. The preliminary study reported here is an initial attempt to develop a sand-bed concentrator. Results are encouraging in the following respects.

- The sand which can be used as a bed material extends from loamy sand to coarse sand, even though coarse sand seems to be better suited for high salt solutions (40 - 80 g L^{-1}).

- For concentrating saline water, the sand layer needs not to be thick, perhaps only 5 cm (2 inches) in most cases.

- The salinity of wastewater which is suitable for 80 to 90% volume reductions can safely extend to 40 g L^{-1}, possibly up to 60 g L^{-1}. This covers most saline wastewater streams generated by industrial or agricultural activities.

- The salinity of the concentrated brine is near the solubility limit of halite, although some safety margin has to be provided to avoid clogging by precipitated salts.

Research Needs. There are at least three aspects which need to be examined prior to designing prototypes.

- Water application control. Salinity of the drainage water is highly dependent of the leaching fraction especially below about 20%. The water application schedules can be estimated first by using the pan evaporation, then the target leaching fraction can be computed from a steady-state salt balance equation. However, it is not easy to obtain the specified leaching fraction, especially at a range below 15%. A micro-processor system may be introduced to fine-tune water application, based on the actual monitoring of the salinity of the drainage water. Poor handling of water application can result in drainage failure or excessive percolation of the saline water applied. Saline water can be applied using conventional ground sprinklers for small applications, and possibly a resin coated center pivot for large applications.

- Drainage collection system. We vision that the concentrated brine from the sand beds will be drained by using some type of drain pipes placed in a gravel layer below. Existing knowledge on drain system designs may be sufficient for designing a drain collection system. Some engineering work is needed for determining cost-effective collection systems.

- Use of salts as a seal. In addition to irrigation and drainage systems, the lining of the sand-bed bottom can be a costly item. Evaporites could form a water-tight seal. Research is needed to explore ways to utilize the contracted brine for providing the bottom seal.

Potential Applications. Detailed designs of a sand-bed concentrator would depend primarily upon how the concentrated brine is to be handled. The following outlines some potential scenarios.

- Saline solar pond application. One of the significant cost items for constructing saline solar ponds is to bring in large quantities of salts. A sand-bed concentrator can be designed to concentrate saline water streams to the salt levels desired for this type of applications. The heat captured can be used to elevate the temperatures of feed water to increase evaporation, especially during winter months.

- Evaporation pond replacement. Existing evaporation ponds with lining can be converted to a sand-bed concentrator by placing a gravel layer with drain pipes and a coarse sand layer with ground sprinklers. The concentrated brine can be further evaporated in the lowest spot within the pond or be piped to a location designated as salt disposal pit(s) or to a brine concentrator to generate salts. Since the rate of water evaporation from sand-beds is lower than from ponded water by 15 to 30%, an additional land area may be required, unless the heating option indicated above is used.

- Dural uses of sand-beds and disposal ponds. Wastewater discharge from industrial sources is often steady, whereas the evaporation rate changes with season by as much as a factor of 2 to 4. This usually means large land area requirements to dispose of the steady flow during winter months. This translates to a large sand bed size and construction cost. One way to deal with this problem would be to utilize halite sludge to heat the feed water as mentioned earlier. Another option would be a dural system of sand-beds and concentrated brine pits. In this system, the sand bed size is assumed to be determined based on the annual average evaporation rate or the evaporation rate during summer months. This usually means the bed size much smaller than the requirement for winter months, perhaps ½ to 1/4 in size, depending on the evaporation rate differences between summer and winter months. The concentrated brine generated from the sand bed during high evaporation period is assumed to be sprinkled in the adjacent salt disposal pits. Since the drainage water from the sand-bed is close to the solubility limit of halite, sprinkling of the drain water should form a layer of halite at the bottom of the disposal pit, which could be used for seal. During the period of low water evaporation, the salt disposal pit can be used as a supplemental area for evaporating the steady waste-water stream. A thin layer of sand, perhaps no more than 1 inch, may be placed initially to reduce water ponding and dissolution of the halite layer below. However, such a system of operation, especially evaporation from salt disposal pits with a thin sand layer must be studied along with the integrity of the halite seal in the presence of water at concentrations below the solubility limit of halite.

7. WORK PERFORMED: PRELIMINARY SCREENING OF SAND-BED MATERIALS AND CONFIGURATIONS

7.1 Methodology

Sand beds to be used for concentrating saline wastewater through evaporation must meet the following basic requirements; I) both saline and rain water must infiltrate readily, ii) can store saline water at quantities sufficient to meet at least daily or bi-daily evaporation losses, iii) minimal restriction for water evaporation, and iv) uniform drainage. In addition, there are some logistic requirements to be met, such as; I) minimal sand hauling to contain the initial costs, ii) flexible sand grain size requirements as much as possible, iii) resistant to shifting and wind erosion, and iv) minimal maintenance problems, especially against dust or salt-caking.

Some of these requirements place contradicting grain size preference. However, it would be reasonable to assume that the material to be placed at the bottom of the bed would be a thin layer of gravels, which allows unrestricted drainage into collection pipes placed over the *geotex* or a layer of water-tight asphalt. The layer above the gravel layer may consist of coarse sand for preventing plugging of the gravel layer. These subgrades have to be stable enough for equipment traffic, and for this reason, crusher chips with an angular-shape may be preferred over round-shaped gravels. The main bed material is assumed to be some type of sand for assuring good infiltration and drainage, yet has the capacity to hold water for subsequent evaporation, and be stable against shifting and wind erosion. The following test was performed for selecting bed materials and configuration, based primarily on water evaporation, retention and evaporation characteristics.

The first set of materials consisted of fine, medium, coarse, and very coarse sand (Table 7-1). The second set consisted of loamy sand and mortar sand (coarse sand) passed through a 2 mm screen. The loamy sand consisted of 65% fine sand and 31% medium sand, while the mortar sand was made of 12, 44, 37 and 7% of fine, medium, coarse, and very coarse sand, respectively. In addition, the loamy sand was passed through a 0.25 mm screen, and the size fraction is referred to as fine sand plus some silt, or, for short, "dust". This fine sand material containing silt was used to evaluate the potential effect of dust-cake on water infiltration and evaporation. Additional materials used for testing included very coarse sand (1 - 2 mm) as mulch, and a chemical sand stabilizer consisting of tree resin with a proprietary additive.

These sand materials were placed in plastic pots (13.0 cm ID at the top and 10.2 cm ID at the bottom) with a depth of 11.5 cm, plus the top clearance of 3 cm. The cross-sectional area of the pots was 132 cm^2 at the top, and 82 cm^2 at the bottom with a mean cross-sectional area of 107 cm^2. The bottom of the pots contained a 1 cm layer of crushed gravel (1 to 4 mm size), thus leaving 10.5 cm for the bed material placement. The sand materials placed were tapped and pressed down lightly to the rim with a disk plunger, leaving 2.5 cm of clearance for irrigation. The corresponding bulk densities are shown in Table 7-1, along with the bed thickness. In the 7th and 8th treatments, a 1 cm layer of a very coarse sand (1 - 2 mm size) was placed as mulch over the 9.5 cm layer of the loamy sand or the mortar sand. In the 9th treatment, a 5.0 cm layer of mortar sand was placed over the 5.5 cm layer of loamy sand. In the 10th and 11th treatments, the dust sample was placed over the loamy sand and the mortar sand at a thickness of 0.5 cm. Additional treatments consisted of the application of the sand stabilizer mentioned earlier. The product was first diluted with water to a ration of 1:10 and another to 1:20 by volume. The solutions were then applied at two rates: 1.5 and 3.0 ml per pot (or 0.11 and 0.23 mm of the 1:10 diluted solution), and 3.0 and 6.0 ml of the 1:20 dilution. These application rates correspond to 100 and 200 L per ha of the concentrated solution. The application of the 1:20 dilution solution at 200 L/ha produced a firm surface crust on mortar sand and a thin friable layer on loamy sand. The application of the 1:10 dilution solution at 200 L/ha or at 100 L/ha produced a thin frail crust which disintegrated upon a touch of a finger tip. In addition, we applied 10 times of these rates, and found that the pore spaces filled with the resin and caused a severe reduction in infiltration rates. Thus, no further testing was performed at these high rates.

The measurement of water holding capacity, intake rates and water evaporation rates were performed in a greenhouse in triplicate. The potted sand was arranged in a block design, because of some unevenness in evaporation rates depending on location within the greenhouse. Three pots filled with tap water at the same depth as the sand were provided so as to measure water evaporation from the free water surface. The first water application was made using 4.7 cm of tap water [salinity of 800 mg L^{-1} and a sodium adsorption ratio (SAR) of 5.5]. This application caused drainage in all cases, and the water holding capacity was measured gravimetrically after the drainage became zero, which took approximately one hr. Water evaporation was monitored daily for the next 3 days by weighing the potted sand. The second water application was made using 1.2 to 2.3 cm of the tap water, and the measurements of water holding capacity, the intake rate, and the evaporation rate were measured. The application of the water at this depth produced a leaching fraction of approximately 20%.

During the 3rd and 4th water application, a saline solution (salinity of 20,000 mg L^{-1} with the SAR of 50) was applied, instead of tap water, at the depths necessary to cause a 20% leaching fraction (Table 7-2). During the 5th water application, distilled water was used. All other procedures were the same as the first two water applications. Thereafter, tapwater was applied to the loamy sand and the mortar sand at a depth of 3.8 cm, and the potted sand was removed at 2.5 cm increments and the soil water content measured for each layer.

The water holding capacity was determined by dividing the water retained by the volume of sand, whereas the water intake and the evaporation were divided by the cross-sectional area of the exposed sand surface. The water intake data were then used to compute the sorptivity by the following equation

$$S = D/t^{1/2} \tag{1}$$

where D is the depth of water or saline solutions applied, and t is the observed time for infiltration. The sorptivity estimated varies with the pore water content prior to irrigation. The triplicated measurements were averaged, and the standard deviation computed. The analysis of variance was made for the block design at a 5% level. The mean separation was made with the Duncans Multiple Range Test at a 5% level.

7.2 Results

Water Holding Capacity. Results of the water holding capacity measurements made after the first and the second water applications are shown in Table 7-3. The water holding capacity after the 3rd and 4th water applications was not different from the 2nd measurement, thus they are not shown. The water holding capacity of fine, medium, and coarse sand did not differ significantly, and averaged 3.8 cm per 10 cm of the bed thickness after the 1st water application. After the 2nd water application, the capacity was reduced to an average of 3.4 cm, probably due to realignments of sand particles. However, the very coarse sand had a significantly lower water holding capacity of 2.1 cm after the 2nd water application. The water holding capacity of the loamy sand and the mortar sand averaged 0.30 cm/cm and were smaller than those of fine, medium or coarse sand fractions by about 25%. The placement of loamy sand below the mortar sand (treatment 9) increased the water holding capacity only by about 10%. Applications of the chemical stabilizer did not affect water holding characteristics to any significant degree.

The vertical distribution of soil water retention in the potted loamy sand and mortar sand did not differ greatly with depths. The water content at the soil surface was 0.29 and 0.30 cm/cm in the loamy sand and mortar sand, respectively, then increased to 0.33 cm/cm at the bottom, which is close to the estimated porosity of 35% in these sand materials.

Water Intake. Recall that the observed water intake data were expressed by the sorptivity unit given by Equation (1). The sorptivity values listed in Table 7-3 can be interpreted as the depth of water infiltration achieved in a period of 1 min. The sorptivity observed in loamy sand ranged from 1 to 1.5 cm /min$^{1/2}$ and that of mortar sand from 2 to 4 cm/min$^{1/2}$. Since the depth of saline water sprinkling per application is likely to be in a range of 1 to 2 cm, water intake may occur in a matter of a minute or two.

There were some significant differences in water intake rate among the sand materials tested. The sorptivity, for example, increased from an order of 2 to 8 cm/min$^{1/2}$

as the size fraction increased from fine sand to very coarse sand. Likewise, the sorptivity of the mortar sand tested was three-times greater than that of the loamy sand. The placement of the dust sample at a thickness of 0.5 cm reduced the sorptivity of the mortar sand by a factor of 3, but not in the loamy sand. The application of the chemical stabilizer did not significantly alter water intake rates. The use of deionized water during the 5th irrigation did not change water intake rate to any significant degree, even when the dust samples were placed on the loamy or the mortar sand.

Water Evaporation. The quantity of water evaporated from the sand surface following the third irrigation with the saline solution is shown as a relative value to the evaporation from the free water surface in Figure 7-1. The evaporation from the water surface ranged from 0.6 to 0.8 cm/day as shown in the figure. Water evaporation decreased with time after irrigation as expected, and was highest in medium sand, followed by fine and coarse sand fractions. The evaporation from the very coarse sand fraction was lower by as much as 50%. The evaporation from the mortar sand was similar to or slightly lower than that from the medium sand, and the evaporation from the loamy sand was similar to that from fine sand. Recall that the main size fraction of the mortar sand is medium sand, and that of the loamy sand is fine sand (Table 7-1).

Water evaporation from the loamy sand and the mortar sands, with or without the mulch or dust placement, is shown in Figure 7-2. The data set shown is from the third irrigation. The placement of dust increased evaporation from the loamy sand and the mortar sand by as much as 15%, presumably because the dust layer retained water near the soil surface. The placement of very coarse sand mulch at a thickness of 1 cm reduced water evaporation by half. The placement of 5 cm layer of mortar sand over the loamy sand also resulted in a major reduction in water evaporation during the 3rd day. It appears that the placement of sand with coarser grain sizes over the sand with smaller grain sizes reduces water evaporation to a substantial degree.

The application of the chemical stabilizer caused only slight reductions in water evaporation in loamy sand, and measurable, but small reductions (<10%) in mortar sand (Figure 7-3).

7.3 Discussion

The most important finding of this preliminary study seems to be the level of water retention observed in a relatively thin layer of sand [10.5 cm] placed over a thin layer of crusher chips. This feature should help reduce the quantities of sand needed for preparing sand-beds. The gravel layer placed below might have shut off the capillary suction, thus allowing the high level of water retention. Water holding capacity of sand materials with an extended depth is very low, typically 0.05 cm/cm or less. Water holding capacity of 0.30 cm/cm usually corresponds to that of loam without the presence of a gravel layer.

From the view of water retention, the choice of sand can be either fine or coarse, as long as it does not enter into the category of very coarse sand. This provides flexibility in bed material selection. However, water intake rates, and to some extent, evaporation rates decrease when fine sand is used. In addition, fine or loamy sand is subject to a greater degree of wind-blowing, until settled with irrigation, whereas coarse sand and mortar sand can be stabilized readily with the chemical stabilizer. If there is a choice, coarse or mortar sand may be better suited as bed material than fine sand or loamy sand. However, trafficability over coarse sand is not any better than over loamy or fine sand. These aspects must be considered prior to making the practical decision.

The thickness of the sand layer used in this experiment was 10.5 cm. The selection of this particular thickness was made with a consideration to provide water storage in the beds in quantities sufficient to last for several days in the events that sprinkling must be halted due to wind. If this is not a concern, it may be possible to reduce the sand layer-thickness. Such a system can reduce the initial cost of hauling sand.

The rate of water infiltration did not decrease to any substantial degree when distilled water was applied, including the treatments involving the surface placement of dust. Poor infiltration and runoff of rain water are common in soils irrigated with saline water. The observation made in this experiment seems to indicate that this problem is not likely to be significant in sand bed.

In making additional interpretation of the data presented, it should be kept in mind that all the data were obtained under the minimal presence of salts in the sand beds. The impact of salts accumulated on water infiltration, drainage and water evaporation is presented in the next section.

8. WORK PERFORMED: TESTING OF BENCH-SCALE SAND-BED CONCENTRATORS

In operating a sand-bed concentrator, it is vision that saline water will be applied through sprinklers or sprayers placed above the sand bed. A center pivot sprinkler system coated with plastic resin such as used in seawater irrigation trials may be an option. Such a system can apply saline water daily or if desired, twice a day at a depth comparable to the daily potential evaporation rate with a high degree of uniformity. The problem caused by wind drift is usually managed by placing the application nozzles close to the ground level, and by providing an automatic shut-down system connected to a wind-speed gauge. The installation and maintenance of such a system is likely to be less costly than subsurface water-feeding systems which are ordinarily required for a sand evaporator intended to collect salts at the surface of sand beds.

From an operational point of view, saline water applied should be concentrated as much as possible for reducing the volume of concentrated brine and for minimizing algae growth. However, saline water applied at low leaching fractions can form salt crusts which can not only reduce water evaporation, but also make the system inoperative. In addition, the formation of halite can impair drainage. The study reported here was conducted to determine the leaching fraction necessary to maintain adequate water infiltration, drainage and evaporation rates, while attaining a desired level of reductions in saline water volume.

8.1 Simplified Water and Salt Balance

The steady-state salt balance in a sand bed can be expressed as

$$C_I D_I = C_D D_D \tag{1}$$

where C and D denote the salt concentration and the depth of water, respectively. Subscript I and D denote irrigation and drainage water, respectively.

Equation (1) can be rewritten as

$$C_D = C_I D_I/(D_I - E) \tag{2a}$$

$$\text{or} = C_I/(1 - E/D_I) \tag{2b}$$

where E is the depth of water evaporation, and E/D_I will be referred to as the evaporated fraction.

By definition, the leaching fraction LF is equal to D_D/D_I, and is related to E/D_I as

$$LF = 1 - E/D_I \tag{3}$$

The relationship between salinity of drainage water (C_D) and the evaporated fraction (E/D_I) or 1 - LF is shown in Figure 8-1. Note that salinity of drainage water remains fairly constant initially, then increases rather sharply.

Salinity of most saline waters from agricultural drains or industrial processes is usually less than that of sea water which is usually 32 g L^{-1}, and the solubility limit of halite is 360 g L^{-1}. Judging from the salinity of drainage water, it appears that salt precipitation as halite from most wastewater would not occur unless the leaching fraction decrease down to a range of 10% or less. However, when salinity for the saline water exceeds that of seawater, halite can form in the drainage water at the leaching fraction greater than 0.1. If an intent is to reduce the volume of saline water by 80% (or the leaching fraction of 0.20), the operational limit of salinity of the saline water may prove to be around 60 g L^{-1}.

The leaching fraction required to maintain the salinity of drainage water below the solubility of halite can be computed as

$$LF = C_I/360 \tag{4a}$$

where the concentration of saline feed water (C_I) is to be expressed in g L^{-1}. The depth of irrigation necessary to attain the desired level of leaching can be computed as

$$D_I = E/(1 - LF) \tag{4b}$$

Note that this equation comes from Equation (3).

The highest level of salt accumulation usually occurs at the surface of sand beds, following water evaporation. Salinity of the surface layer following irrigation can be estimated as

$$C_{sf} = C_S\, E/wL \tag{5}$$

where C_{sf} is the salinity of the surface layer with a thickness of L and the water holding capacity of w, and C_S the salinity of pore water evaporated.

Salinity of pore water evaporated can be expressed as

$$C_S = (n\, C_I + C_D)/(n+1) \tag{6}$$

where n is an empirical matching factor.

Substituting Equation (2b) into Equation (6)

$$C_S = [n\, C_I + C_I/(1 - E/D_I)]/(n + 1) \tag{7}$$

Substituting Equation (7) into Equation (5)

$$C_{sf} = C_I\, E[n + 1/(1 - E/D_I)]/(n + 1)\, wL \tag{8}$$

According to Equation (8), salinity of pore water in the surface layer increases with increasing evaporation (E), salinity of irrigation water (C_I), and the evaporated fraction (E/D_I) or the leaching fraction which is equal to $1 - E/D_I$. Such relationships are shown in Figure 8-2 when E, wL and n were assumed to be 1 cm, 0.25 cm and 2.0, respectively. Under these conditions, it appears that halite precipitation can occur at leaching fractions greater than 0.2 when salinity of feed water exceeds about 40 g L^{-1}.

Halite precipitation is likely to increase the potential for pore plugging and subsequent reduction in water infiltration and evaporation. However, its impact on water infiltration and evaporation is likely to be governed by the quantity and locations of halite precipitated more so than by C_S. The quantity of halite precipitation may be estimated as

$$Q_H = 0.001\ wL\ (C_{sf} - C_H)/b \tag{9}$$

where Q_H is the volume of halite precipitation per unit sand-bed surface (e.g., ml/cm^2), C_H the solubility limit of halite (360 g L^{-1}), b the bulk density of halite (2.16 g cm^{-3}), and C_{sf} is defined by Equation (8). The numerical factor of 0.001 is applied to convert the salt concentration unit from g L^{-1} to g mL^{-1}.

Estimated quantities of halite precipitation are shown in Figure 8-3, when wL and E were assumed to be 0.25 cm and 1 cm, respectively. The extent of halite precipitation would increase in proportion to water evaporation. At an assumed water evaporation of 1 cm, the estimate shows that halite precipitation from ordinary saline wastewater applied at a leaching fraction of 0.2 would occupy small spaces as compared to the typical pore space of 0.36 ml cm^{-2}. This may suggest that water infiltration could be maintained under high frequency irrigation at a leaching fraction of about 0.20. When the leaching fraction is reduced to 0.10 or the evaporated fraction of 0.9, (which is noted by a light vertical line in Figure 8-3), the quantities of halite precipitated at the bed surface can reach as much as 10% of the total sand bed surface area, and could result in a modest reduction in water infiltration when salinity of the saline feed water is as high as 80 mg L^{-1}.

The quantities of halite which may deposit at the soil surface will increase substantially if irrigation is discontinued. When saline water containing 40 g L^{-1} of NaCl has been evaporated at a leaching fraction of 0.20, for example, the salinity of pore water would be in the order of 100 g L^{-1}. If all of the salts accumulate at the soil surface upon the evaporation of 3 cm of the solution, the quantity amounts to 0.3 g cm^2 or 0.16 ml cm^{-2}, which occupies about half of the pore spaces if they deposit in the pore spaces. If they deposit on the top of sand grains, however, the effect on water infiltration is likely to be minimal.

In addition to halite, Ca salts precipitate readily as $CaCO_3$ or $CaSO_4 \cdot 2H_2O$ (Table 8-1). In most instances, $CaCO_3$ precipitation is likely to occur in storage ponds, but some may also precipitate in sand beds. The extent of Ca precipitation is more or less predictable with computer models, but is uncertain if precipitated Ca salts remain in the sand bed or percolate through, as the pore spaces in sand beds are much larger than the freshly precipitated crystal sizes of $CaCO_3$ or $CaSO_4 \cdot 2H_2O$.

8.2 Methodology

The mortar sand and the loamy sand described in the preliminary screening test were used for this study. They were packed into plastic pots (13 cm ID at the top and

10.2 cm at the bottom) at layer thicknesses of 5.0 and 10.5 cm over a layer of crusher chips (1 - 4 mm size), using the same procedures as those used in the preliminary screening tests. The water holding capacity of the 5 cm mortar sand was 1.9 cm/5 cm, and that of the 10.5 cm mortar sand was 3.9 cm/10.5 cm.

Five saline solutions containing NaCl at concentrations ranging from 20 to 80 g L^{-1} were prepared by adding NaCl to distilled water (Table 8-2). In one case, 2 g of $CaSO_4 \cdot 2H_2O$ was added to 1 liter of a solution containing 20 g L^{-1} of NaCl. The quantity of $CaSO_4 \cdot 2H_2O$ added was close to the solubility limit of gypsum in nonsaline water. The solubility of gypsum increases with increasing the ionic strength of saline solutions.

The potted sand was placed in a greenhouse, then irrigated from the surface, and in selected cases, they were subirrigated (Table 8-3) by the procedures described below. The leaching fraction for the surface-irrigated cases was targeted at 0.20 for the first 4 weeks, then 0.10 following a drying treatment of 4 weeks.

<u>Surface-irrigated</u>. The saline solutions were applied to the surface of potted sand. A sheet of thin plastic disk was placed on the sand surface to avoid surface disturbances during solution applications, and the sheet was removed as soon as solution applications were completed. The depth of solution application was to attain a leaching fraction of 20% for the first 4 weeks, and 10% for the remaining 4 weeks. However, the actual leaching attained was somewhat different from the intended as shown in Table 8-4. The time required for applying the solutions was recorded, and the data were used to compute the sorptivity as described earlier. The rate of water evaporation was determined by measuring weight losses after the drainage was completed. Drainage from potted sand was collected, and determined for its volume and salinity. Salinity of drainage water was determined by measuring the electrical conductivity (EC). The relationship between the electrical conductivity (EC), and salinity (C) is not entirely linear in a high range of salinity. It was determined that the following power function approximates the relationship.

$$C = a\,EC^b \tag{10}$$

where a and b are characteristic coefficients determined through calibration against the solutions of known concentrations.

Upon the completion of the 28th day irrigation, water application was temporarily discontinued for a period of 4 weeks, and the potted sand was left to dry. This caused white salt precipitation to cover the entire sand surface. Water application was reactivated at an intended leaching fraction of 10% on the 29th irrigation day. The experiment continued for another 4 weeks, and water infiltration and evaporation measured as before. The potted sand was then sectioned every 2.5 cm as soon as water application was completed.

Subsurface-irrigated. Potted mortar and loamy sand were also subirrigated by placing them in a shallow pan of water. The water level in the pan was kept approximately 9 cm below the surface of the sand, and water evaporation from the pan was prevented by placing a sheet of plastic and aluminum foil. The water evaporated from the sand surface was monitored by weighing the potted sand and the pan daily, and the solutions were added to the pan in quantities to make up the losses with a correction for their densities. This experiment was conducted for a period of 57 days, excluding the 4 weeks of the drying period. All of the measurements were carried out in triplicate.

Evaporation From Ponded Water. Evaporation from the free water surface was also determined using the identical pot filled with distilled water and saline solutions containing 40 and 80 g L^{-1} of NaCl. The water level was adjusted daily to the same level as that of the sand by adding distilled water.

8.3 Results

Water Infiltration. The sorptivity into dry sand measured at the onset of the experiment averaged 3.3 cm $min^{-1/2}$ in the mortar sand, and 1.6 cm $min^{-1/2}$ in the loamy sand (Table 8-5). These sorptivity values differ somewhat from those reported during the preliminary screening tests (Table 8-2). The differences can be attributed to slight differences in the packing procedures and the fact that the sand samples used for the second experiment were not identical, but came from a separate batch. Thereafter, the sorptivity into the mortar sand and the loamy sand irrigated daily has decreased to around 1.5, and 0.7 cm $min^{-1/2}$, respectively, whereas the sorptivity in the mortar sand irrigated bi-daily or having a layer thickness of 5 cm remained higher (Table 8-5). In all cases, the sorptivity measured was lower than the figures reported during the preliminary tests (Table 8-2). These differences can be attributed to the difference in pore water depletion prior to irrigation. As indicated earlier, the sorptivity decreases with reducing pore water depletion prior to irrigation.

Salt deposition at the bed surface began to appear starting at the 2nd week in the treatments involving 60 and 80 g L^{-1} solutions. Meantime, the sorptivity, including the one from the treatment with distilled water, has steadily declined, and has settled around 1.2 cm $min^{-1/2}$ in the mortar sand, and less than 0.5 cm $min^{-1/2}$ in the loamy sand by the end of the 20% leaching period (Table 8-5). Irrigation with the 20 g L^{-1} solution containing gypsum had no effect on water infiltration. The sorptivity into the mortar sand irrigated bi-daily remained higher. Slight algae growth was noted only in the treatment involving distilled water. The decline in sorptivity observed may be attributed to a combination of sand particle realignment, salt accumulation, and above all, a general increase in pore water contents prior to irrigation, due to a general decline in evaporation rate discussed in a later section.

The drying of the sand beds after the 28th irrigation caused white salt accumulation on the entire bed surface, except in the treatment involving distilled water. However, the sorptivity measured after the drying period registered the values almost equaling the initial sorptivity into the mortar sand with no salt accumulation (Table 8-5). It is thus apparent that the salts accumulated at the surface sand did not affect water infiltration in the mortar sand. In the case of loamy sand, however, the sorptivity did not fully recover (Table 8-5). The salt accumulation in the mortar sand was a form of frost with visible crystal developments on the sand grains, whereas in the loamy sand, the crystal development was less apparent. In both cases, the surface accumulated salts disappeared after the 29th irrigation using approximately 3 cm of applicable solutions. The sorptivity has remained fairly constant for the next 12 days under the 10% leaching fraction (Figure 8-4). Thereafter, it decreased for a period of about 5 days when the evaporation declined. The sorptivity increased again upon the increases in evaporation rate, and has settled at approximately 1 cm $\text{min}^{-1/2}$ in the mortar sand and less than 0.5 cm $\text{min}^{-1/2}$ in the loamy sand during the final days of the experiment involving a 10% leaching fraction (Figure 8-4 and Table 8-5).

Drainage. Salinity of the drainage water from the mortar sand and the loamy sand increased with repeated irrigations, and reached a plateau by the end of the 20% leaching process for the irrigation solutions containing 20 and 40 g L^{-1}. Otherwise, the steady-state condition was not quite achieved (Figure 8-5). Lowering the leaching fraction from 0.20 to 0.10 resulted in additional increases in salinity of the drainage water, and led to the complete seal of the drain holes by halite deposition when irrigated with the 80 g L^{-1} solution, even though the drain holes, 4 each per pot, were as large as 0.5 cm in diameter. The day when the drainage ceased is marked in the figure.

Salinity of the drainage water from the loamy sand was similar to that from the mortar sand except at salinity of 22 g L^{-1}, containing gypsum (Figure 8-2). The actual leaching fraction from the loamy sand irrigated with this water source was lower than that from the mortar sand, thus resulted in higher salinity in the drainage water. It is entirely possible that gypsum has precipitated in the bed, and reduced drainage.

Salinity of the drainage water from the mortar sand irrigated bi-daily was lower by 10 to 15% when compared against salinity under daily irrigation (Table 8-6). Salinity of the drainage water from the mortar sand with a layer thickness of 5.0 cm was also lower than that of 10 cm by 5 to 10% (Table 8-6). These differences can be accounted for by the differences in leaching fraction. The measured salinity was lower than the predicted by the steady-state salt balance equation, Equation (2b), when salinity of irrigation solutions was higher than 40 g L^{-1}, presumably because the steady-state conditions were not achieved.

Evaporation. Water evaporation from the ponded solutions ranged mostly from 0.5 to 0.8 cm/day for the first 3 weeks, than has fluctuated widely (Figure 8-6), which included an unusually low period due to the passage of a series of cold fronts. There was a little difference in evaporation from the solutions tested; which included 40 and 80 g L^{-1}. The overall pattern indicates a general trend of progressive reductions in evaporation from ponded water over the experimental period. Figure 8-6 also include examples of water evaporation from the mortar sand (10.5 cm) irrigated daily. The evaporation from the mortar sand fluctuated in a manner which paralleled the evaporation from ponded water, but with progressively lower rates with increasing salinity of the solutions applied.

The evaporation from sand beds was then normalized by the evaporation from the ponded distilled water, and it will be referred to as the relative evaporation. The relative evaporation from the mortar sand (10.5 cm) irrigated with distilled water fluctuated around 0.8, whereas the relative evaporation from the cases involving saline solutions has progressively reduced (Figure 8-7). This pattern of progressive evaporation reduction from the solutions containing 60 and 80 g L $^{-1}$ was more evident in the loamy sand than in the mortar sand. Upon the completion of the 29th irrigation following the drying process, the relative evaporation increased somewhat. Some of these increases have occurred during the period of the low evaporation demand which provided high pore water contents. The evaporation from the mortar sand irrigated bi-daily was similar to that from daily irrigation when salinity of the saline solution was 20 g L $^{-1}$ (Figure 8-8). However, at salinity levels of 40 and 60 g L $^{-1}$, the evaporation from bi-daily irrigation was lower by as much as 20%, presumably due to higher levels of salt accumulation at the bed surface. The evaporation from the mortar sand with a layer thickness of 5 cm was greater by about 10% than the case of 10.5 cm under daily irrigation.

The evaporation from the mortar sand and the loamy sand subirrigated constantly with distilled water remained a fairly constant rate of 0.9 in relative evaporation (Figure 8-9). The evaporation from the bed subirrigated with saline solutions, especially at concentrations of 60 and 80 g L $^{-1}$ was greatly lower, and steadily declined especially after the drying period. When compared against the evaporation from the surface irrigated cases (Figure 8-7), the evaporation from subirrigated beds was lower by half when highly saline solutions (60 and 80 g L $^{-1}$) were used. In the case of distilled water, the differences in evaporation between the two methods of irrigation were not significant.

Salt accumulation at the surface of the bed subirrigated with saline solutions did not show crystal developments at first, but formed an icy sheet of crust. Upon the drying treatment, white salt crystals developed at the surface of the mortar sand, which then developed into a thick frost (2- 3 mm) at 80 g L $^{-1}$, whereas in the loamy, it turned into an icy crust of 1 or 2 mm by the end of the experiment. In both cases, salt crusts were too thin and frail to remove, except as small fragments.

8.4 Discussion

One of the primary concerns we had was the potential infiltration reduction caused by the salt precipitated at the bed surface, especially when the leaching fraction is reduced to as low as 0.10. The sorptivity indeed declined with repeated irrigations (Table 8-5 and Figure 8-4). However, the sorptivity also declined with application of distilled water, and recovered after the drying process, except in the loamy sand irrigated with saline solutions containing 60 and 80 g L^{-1}. In these high salt solutions, salt accumulation estimated in Figure 8-3 might have affected water infiltration. In other cases, the observed reduction in sorptivity may have occurred largely due to increased pore water contents prior to irrigation, and possibly due to sand particle realignment and settlement.

The magnitude of solution intake remained around 1 cm $min^{-1/2}$ in the mortar sand, and 0.2 to 0.4 cm $min^{-1/2}$ in the loamy sand. Under high frequency water applications involving daily or bi-daily irrigation, the quantities of irrigation are likely to be less than one cm or two. This means that saline water should infiltrate in a matter of one minute or two in mortar or coarse sand, and a few minutes in loamy sand. Unless algae growth or dust-cakes develop on the bed, salt accumulation *per se* is unlikely to induce severe water infiltration problems under high frequency irrigation of most saline wastewater with salinity below 40 g L^{-1}. This includes saline water nearly saturated with gypsum.

The precipitation of halite in drainage water can make the system inoperative as experienced in this test with the solution containing 80 g L^{-1} of halite at a 10% leaching. In theory, saline waters exceeding 72 g L^{-1} are to be used, the leaching fractions greater than 20% should be provided (Figure 8-1). This means that such high salt solutions can be reduced up to 80% in volume. Most saline water sources from industrial and agricultural activities have salinity below that of seawater (32 g L^{-1}). Therefore, it is unlikely that drainage problems appear as long as the leaching fraction is maintained to avoid halite formation in the drainage water, using Equation (4a).

While salt accumulation in sand beds affected water infiltration and drainage, the most significant impact occurred on water evaporation, when saline solutions exceeded 60 g L^{-1} in concentration (Figure 8-7). This problem was particularly severe in the loamy sand. At the same time, the use of the thinner layer of mortar sand essentially alleviated this problem (Figure 8-8). The greater evaporation which occurred in the mortar sand with a 5.0 cm layer may be attributed to the fact that pore water was retained near the surface. A thin layer sand bed also offers an advantage of reduced sand hauling and potentially improved trafficability. However, the thickness cannot be reduced excessively, since it lowers the water holding capacity.

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Table 4-1. Annual water use by halophytes irrigated with a mixture of well water and blowdown water at the Ocotillo Power Plant, Tempe, Arizona.

Water use (meters)	*Atriplex nummularia*		*Paspalum distichum*		*Paspalum vaginatum*	
	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2
1995	1.52	1.32	1.51	1.26	1.63	1.40
1996	2.30	1.98	1.76	1.46	1.82	1.62
1997	2.30	2.16	1.86	1.56	1.87	1.68
1998	2.50	2.51	1.62	1.52	1.59	1.46
Mean	2.08 (S.E. = 0.12)		1.57 (S.E. = 0.07)		1.63 (S.E. = 0.07)	

ANOVA Results:

Variable	F	P	LSD
Site	6.69	0.016	0.16
Year	8.10	0.0007	0.22
Plant Type	17.8	0.0001	0.19
Year x Plant Type	3.26	0.0173	-

Table 4-2. End-of-season, soil moisture levels (0-5 m depth) in plots irrigated with a mixture of well water and blowdown water at Ocotillo Power Plant, Tempe, Arizona. The readings are the mean of data collected in September each year. Results were analyzed separately by soil depth but only the means across depths are presented in this table (see Table 3 for variation by depth). Means followed by a different letter are significantly different at P<0.05.

Soil Moisture Content (%)	*Atriplex nummularia*	*Paspalum distichum*	*Paspalum vaginatum*
1995	11.1(0.8)a	10.4 (0.6)	9.5 (0.8)
1996	11.1 (0.8)a	10.0 (0.5)	9.5 (0.8)
1997	8.9 (0.8)b	9.7 (0.6)	9.4 (0.8)
1998	12.1 (0.8)a	9.8(0.5)	9.9 (0.8)

ANOVA Results:

Variable	F	P	LSD
Depth	9.08	<0.0001	1.36
Year	5.14	0.0005	1.15
Plant Type	4.95	0.0076	0.89
Depth x Plant Type	2.72	0.0016	-

Table 4-3. Soil moisture levels at different soil depths in plots irrigated with a mixture of well water and blowdown water at Ocotillo Power Plant, Tempe, Arizona, 1998. The "Before" values are the mean of September readings during the irrigation season. The "After" values were taken November 4, 1998, after plots had not been irrigated for approximately one month. Within a species, Before and After readings at a given soil depth are significantly different if followed by different letters.

	Atriplex nummularia		*Paspalum Distichum*		*Paspalum vaginatum*	
Soil Depth (m)	Before (% Moisture)	After (% Moisture)	Before (% Moisture)	After (% Moisture)	Before (% Moisture)	After (% Moisture)
0.3	12.7a	8.6b	12.4a	8.24b	12.4a	8.4b
0.6	10.8a	7.8b	10.3a	7.0b	11.5a	7.2b
0.9	11.3a	8.1b	10.7a	6.8b	9.6a	6.0b
1.5	11.9a	9.3b	9.3a	6.9b	9.4a	7.4b
2.5	12.7a	10.6b	10.0	9.1	10.3	9.4
3.1	9.6a	7.8b	7.6	6.9	5.3	5.1
4.0-5.0	15.9	15.1	8.4	7.9	10.6	10.2
Mean	12.1a	9.6b	9.8a	7.6b	9.9a	7.7b

ANOVA Results:

Variable	F	P	LSD
Soil Depth	3.28	0.005	2.17
Sample Date	15.4	0.0001	1.16
Plant Type	5.84	0.0037	1.42

Table 4-4. Mean soil moisture and sodium content (averaged across soil depths) in plots irrigated for 4 years with a mixture of well water and blowdown water at Ocotillo Power Plant, Tempe, Arizona. Samples were taken at the end of the 1998 irrigation season. Moisture content and sodium content were used to calculate the salinity of the soil moisture, and this value was used to calculate the leaching fraction based on the sodium content of the irrigation water (225 mg/L).

	A. nummularia		*Paspalum spp*. (Combined results)	
Mean Moisture Content (%)	12.1		9.8	
Mean Sodium Content (mg/kg)	451		354	
Sodium in Soil Moisutre (mg/L)	3,727		3,593	
Leaching Fraction (%)	6.03		6.26	
Projected Sodium Content at Irrigation Salinity of:	Soil Basis (mg/kg)	Soil Moisture Basis (mg/L)	Soil Basis (mg/kg)	Soil Moisture Basis (mg/L)
500 mg/L (well water)	263	2,169	206	2,084
4100 mg/L (blowdown water)	2157	17,826	1,689	17,235

Table 7-1. Characteristics of bed materials used for the preliminary performance testing.

Materials	Particle sizes	Bulk density	Bed Thickness	Thickness mulch
	mm	kg L^{-1}	cm	cm
1. Fine sand	0.10 - 0.25	1.61	10.5	0
2. Medium sand	0.25 - 0.50	1.59	10.5	0
3. Coarse sand	0.50 - 1.00	1.55	10.5	0
4. Very coarse sand	1.00 - 2.00	1.53	10.5	0
5. Loamy sand (fine 65%, med. 31%)		1.60	10.5	0
6. Mortar sand (med. 44%, coarse 37%)		1.67	10.5	0
7. Mulch over Loamy sand		1.60	9.5	1.0
8. Mulch over Mortar sand		1.66	9.5	1.0
9. Mortar over Loamy sand		1.62	7.0	3.5
10. Dust over Loamy sand		1.60	10.0	0.5
11. Dust over Mortar sand		1.67	10.0	0.5
Loamy sand with Stabilizer				
1:10 dilution				
12. Low rate (100 L ha^{-1})		1.60	10.5	0.0
13. High rate (200 L ha^{-1})		1.60	10.5	0.0
1:20 dilution				
14. Low rate (100 L ha^{-1})		1.60	10.5	0.0
15. High rate (200 L ha^{-1})		1.60	10.5	
Mortar sand with Stabilizer				
1:10 dilution				
16. Low rate (100 L ha^{-1})		1.67	10.5	0.0
17. High rate (200 L ha^{-1})		1.67	10.5	0.0
1:20 dilution				
18. Low rate (100 L ha^{-1})		1.67	10.5	0.0
19. High rate (200 L ha^{-1})		1.67		
20. Water		1.00	11.5	0.0

Table 7-2. The types and quality of water used for the preliminary performance testing.

Water application	Types of water	Salinity		Sodicity SAR	Depth[1]	Soil moisture before water application
		ppm	dS m^{-1}		cm	kg L^{-1}
1st	tap	800	1	3.5	3.78	0
2nd	tap	800	1	3.5	1.2 - 2.3	0.23
3rd	saline	20,000	27	50	1.0 - 1.9	0.20
4th	saline	20,000	27	50	1.2 - 2.2	0.20
5th	deionized	0	0	0	1.0 - 1.9	0.20

[1] Depth is calculated by the cross-sectional area at the top, and was sufficient to refill the depletion and provided drainage at 20% or more.

Table 7-3. The water holding capacity and the intake rates observed under repeated irrigations during the preliminary performance testing.

		Water holding		Intake rate (sorptivity)			
		1st	2nd	1st	2nd	3rd	5th
		---cm/10cm---			cm min$^{-1/2}$		
1.	Fine sand	3.7	3.4	2.4	1.7	1.5	1.6
2.	Medium sand	3.8	3.4	4.8	3.1	2.5	2.9
3.	Coarse sand	3.8	3.2	6.1	3.9	3.1	3.8
4.	Very coarse sand	2.8	2.1	7.3	7.0	7.0	3.7
5.	Loamy sand	3.1	2.9	1.4	1.1	0.8	0.7
6.	Mortar sand	3.3	3.1	3.9	3.0	2.7	2.3
7.	Mulch over Loamy sand	3.0	2.7	1.5	1.0	0.7	1.3
8.	Mulch over Mortar sand	3.0	2.7	3.5	-	-	3.1
9.	Mortar over Loamy sand	3.3	3.2	2.0	1.4	1.2	2.1
10.	Dust over Loamy sand	3.1	2.9	1.1	0.8	0.7	0.7
11.	Dust over Mortar sand	3.1	3.0	2.1	1.5	1.3	1.2
Loamy sand with Stabilizer							
	1:10 dilution						
12.	Low rate (100 L ha^{-1})	3.1	3.0	1.4	1.3	1.1	0.7
13.	High rate (200 L ha^{-1})	3.2	3.0	1.5	1.1	1.1	0.8
	1:20 dilution						
14.	Low rate (100 L ha^{-1})	3.1	3.0	1.5	1.2	1.1	0.7
15.	High rate (200 L ha^{-1})	3.3	3.2	1.5	1.2	1.1	0.8
Mortar sand with Stabilizer							
	1:10 dilution						
16.	Low rate (100 L ha^{-1})	3.1	3.0	3.3	2.9	2.5	1.7
17.	High rate (200 L ha^{-1})	3.1	3.0	3.5	3.1	2.5	1.8
	1:20 dilution						
18.	Low rate (100 L ha^{-1})	3.1	3.0	3.8	3.0	1.9	1.9
19.	High rate (200 L ha^{-1})	3.0	3.0	3.6	3.0	1.9	1.9

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Table 8-1. Solubility of common evaporites formed upon the evaporative concentration of saline wastewater.

Evaporites	Chemical Formula	Mol. weight	Solubility 25C g L^{-1}	Solubility 25C meq L^{-1}
Calcium Carbonate	$CaCO_3$	100	0.014	0.28
Calcium Sulfate	$CaSO_4 \cdot 2\ H_2O$	172	2.41	28
Calcium Chloride	$CaCl_2 \cdot 2\ H_2O$	147	1000.	13,605
	$CaCl_2 \cdot 6\ H_2O$	219	5360.	48,950
Magnesium Carbonate	$MgCO_3 \cdot 5\ H_2O$	174	3.75	43
Magnesium Sulfate	$MgSO_4 \cdot 7\ H_2O$	246	710	5,772
Sodium Chloride	NaCl	58	360	6,200
Sodium Sulfate	$Na_2SO_4 \cdot 10H_2O$	322	927	5,760

Table 8-2. The composition of saline solutions used for the performance testing.

	TDS	EC	Na		Cl		Ca		SO_4	
		dS m^{-1}	ppt	meq L^{-1}	ppt	meq L^{-1}	ppt	meq L^{-1}	ppt	meq L^{-1}
	ppt									
1	20	40	7.9	344	12.1	344	0	0	0	0
2	22	34	7.9	344	12.1	344	0.46	23	1.13	23
3	40	60	15.8	688	24.2	688	0	0	0	0
4	60	84	23.7	1032	36.3	1032	0	0	0	0
5	80	110	31.6	1374	48.4	1376	0	0	0	0

Table 8-3. The outline of the treatments used for the performance testing.

Solution Application Bed Specification	Bed Thickness	Salinity of the saline solutions applied					
	cm	--------- g L^{-1}--------					
Surface Application							
Mortar sand	10.5						
Daily		0	20	22[1J]	40	60	80
Bidaily		0	-	22[2]	40	60	80
Mortar sand	5.0						
Bidaily		-	-	22[2]	40	60	-
Loamy sand	10.5						
Daily		-	-	22[2]	40	60	80
Subsurface Application							
Mortar sand	10.5						
Constant		0	-	22[2]	-	60	80
Loamy sand	10.5						
Constant		0	-	22[2]	-	60	80
Ponded Solutions							
Constant		0	-	-	40	-	80

[1J] This solution contained 20 g L^{-1} of NaCl and 2 g L^{-1} of $CaSO_4 \cdot 2H_2O$

Table 8-4. The depth of saline solutions applied to the sand surface during the performance testing.

Irrig. No	Target LF	Mean Evap	Irrigation Depth		Actual LF	
			Daily	Bi-daily	Daily	Bidaily
		cm/day	-----------cm-----------			
Mortar sand (10.5 cm)						
1	0.20	0.80	3.8	3.8	0.23	0.23
2 - 28	0.20	0.55	0.5 - 0.9	0.6 - 1.5	0.18 - 0.22	0.21 - 0.25
29	0.20	0.54	3.0	3.0	0.12 - 0.24	0.18 - 0.25
30 - 57	0.10	0.41	0.2 - 0.8	0.3 - 1.5	0.08 - 0.15	0.02 - 0.18
Mortar sand (5.0 cm)						
1	0.20	0.80	3.8	-	-	-
2 - 28	0.20	0.55	0.6 - 1.1	-	0.19 - 0.20	-
29	0.20	0.54	3.0	-	0.21 - 0.25	-
30 - 57	0.10	0.41	0.3 - 0.9		0.05 - 0.12	
Loamy sand (10.5 cm)						
1	0.20	0.80	3.8	-	-	-
2 - 28	0.20	0.55	0.4 - 0.8	-	0.17 - 0.19	-
29	0.20	0.54	3.0	-	0.12 - 0.21	-
30 - 57	0.10	0.41	0.1 - 0.7	-	0.05 - 0.12	-

Table 8-5. The sorptivity measured during selected irrigation events during the performance testing.

Bed Specification	Sorptivity during specified Irrigation					
Salt Conc	Initial	3rd	25-27th[1J]	29th[2J]	30-34th	54 - 58th[3J]
g L-1	cm $min^{-1/2}$					
Mortar Sand (10.5 cm), Daily Surface Irrigation						
0	3.4	1.8	1.5	3.3	1.3	1.2
20	3.2	1.7	1.3	2.9	1.0	1.0
22 ($CaSO_4$)	3.3	1.6	1.3	2.7	1.0	1.0
40	3.2	1.5	1.2	3.2	1.0	1.0
60	3.2	1.4	1.1	2.7	0.9	0.9
80	3.2	1.4	1.1	2.7	0.9	0.8
Mortar Sand (10.5 cm), Bi-daily surface irrigation						
22 ($CaSO_4$)	3.2	2.2	1.8	3.0	1.7	1.7
40	3.3	2.1	1.6	3.1	1.3	1.4
60	3.2	2.0	1.7	3.2	1.2	1.2
80	3.2	2.0	1.6	3.1	1.2	1.2
Mortar sand (5.0 cm), Daily Surface Irrigation						
22 ($CaSO_4$)	3.2	1.7	1.3	3.0	1.1	1.0
40	3.2	1.7	1.4	3.2	1.2	1.1
60	3.2	1.6	1.3	3.0	1.1	1.0
Loamy sand (10.5 cm), Daily Surface Irrigation						
22 ($CaSO_4$)	1.6	0.8	0.5	1.3	0.4	0.4
40	1.6	0.7	0.4	1.1	0.4	0.3
60	1.7	0.6	0.3	0.7	0.2	0.3
80	1.7	0.6	0.3	0.7	0.2	0.2

[1J] Correspond to irrigations made toward the end of 20% leaching process

[2J] 29th irrigation was made following the drying process

[3J] Correspond to irrigations made toward the end of 10% leaching process

Table 8-6. Targeted and measured salinity of drainage water from surface-irrigated sand beds toward the end of the targeted leaching irrigation period of 4 weeks.

	Leaching Fraction		Salinity	
	Targeted	Actual	Predicted	Measured
			---------------g L^{-1}--------------	
Mortar sand (10.5 cm), Daily surface irrigation				
0	0.2	0.18	0	0
20	0.2	0.19	100	110
22	0.2	0.18	110	130
40	0.2	0.19	200	210
60	0.2	0.21	300	270
80	0.2	0.22	400 (H)[1J]	290
Mortar sand (10.5 cm), Bi-daily surface irrigation				
22	0.2	0.21	110	90
40	0.2	0.25	200	150
60	0.2	0.23	300	240
80	0.2	0.25	400	270
Mortar sand (5.0 cm), Daily surface irrigation				
22	0.2	0.20	110	100
40	0.2	0.19	200	210
60	0.2	0.20	300	260
Loamy sand (10.5 cm), Daily surface irrigation				
22	0.2	0.17	110	130
40	0.2	0.18	200	210
60	0.2	0.19	300	280
80	0.2	0.19	400 (H)	290

[1J] (H) indicates actual or predicted halite precip.

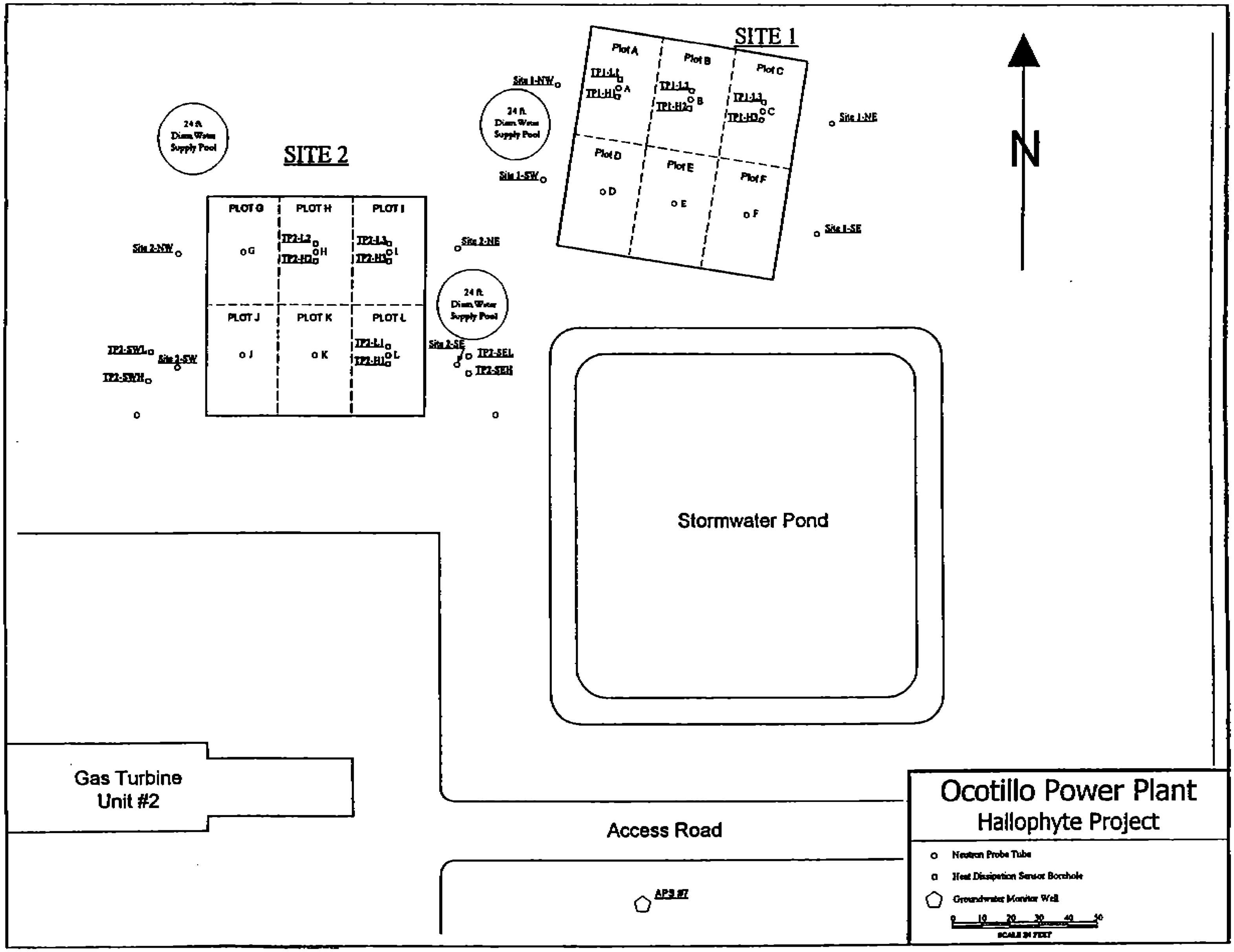

Figure 4-1. Layout of halophyte plots at the Ocotillo Power Plant. *Atriplex nummularia* was in plots A, D, G, and H; *Paspalum distichum* was in B, F, K, and L; and *Papalum vaginatum* was in E, C, I, and J.

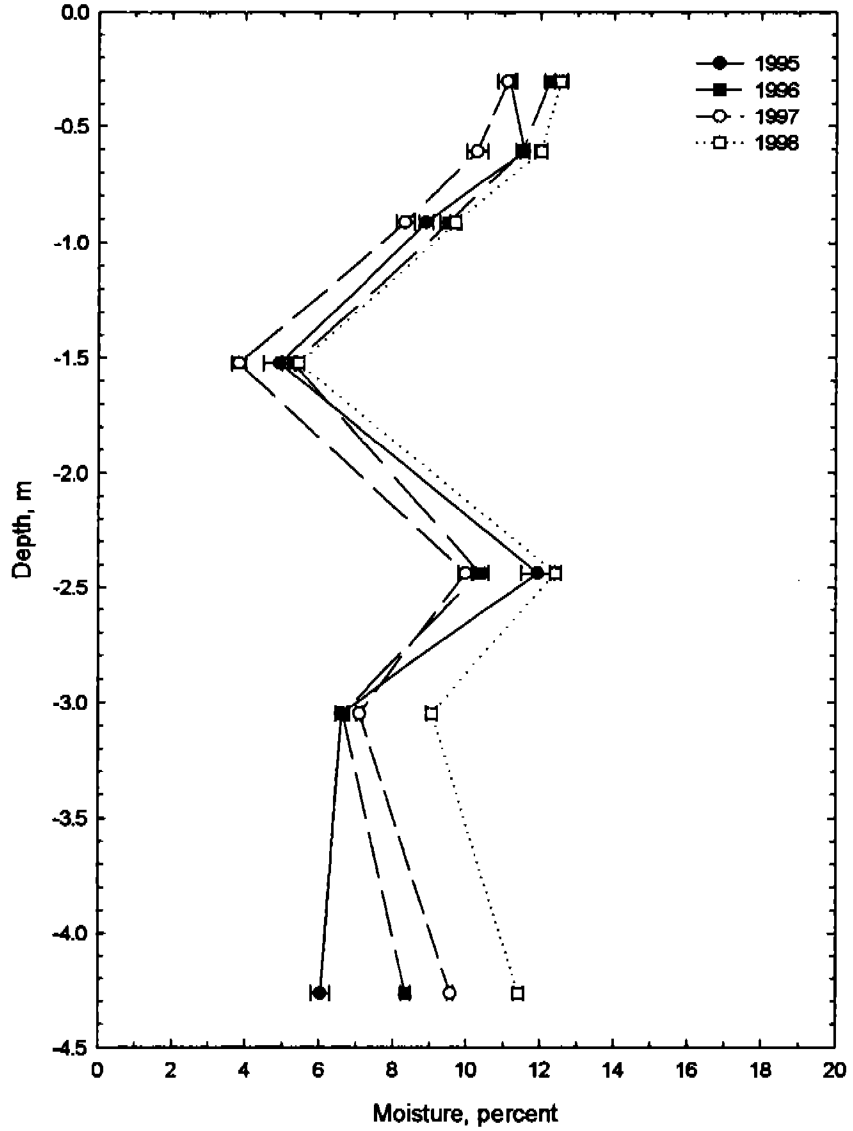

Figure 4-2. Moisture profile, *Atriplex*, Plot A, Site 1

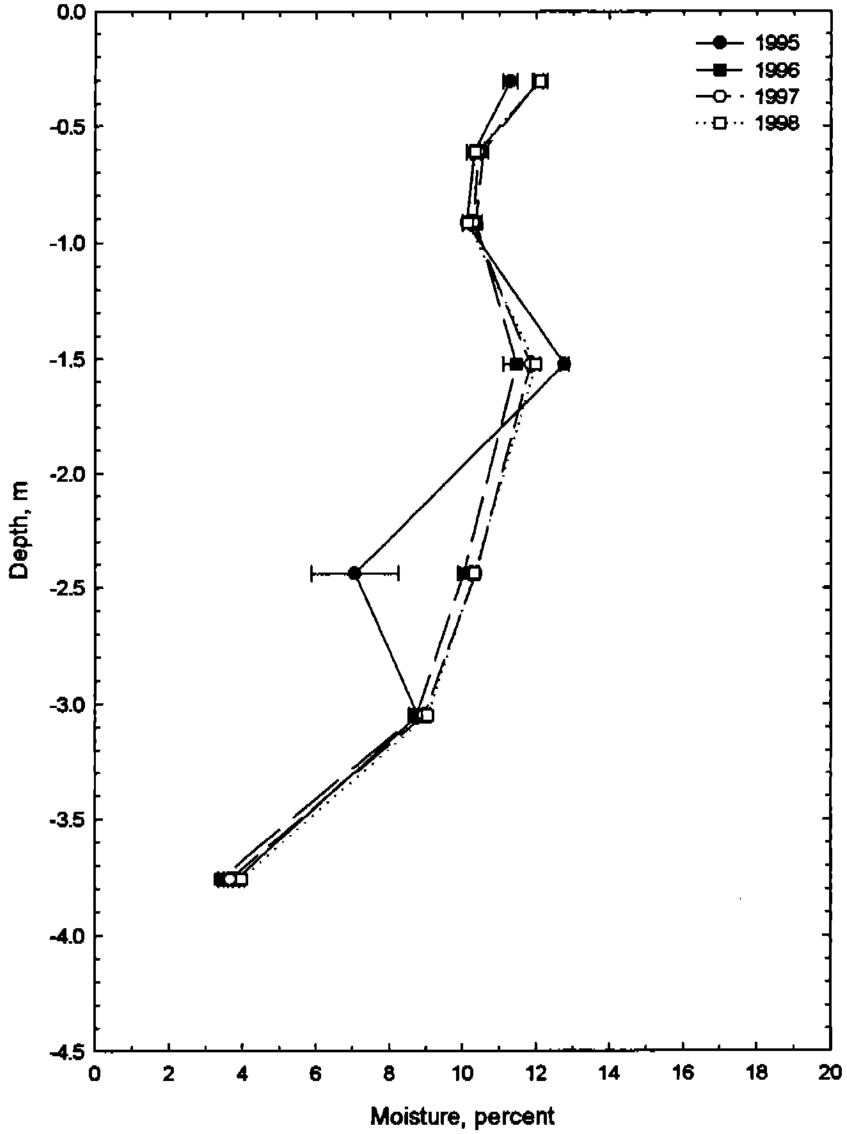

Figure 4-3. Moisture profile, *Paspalum*, Plot F, Site 1

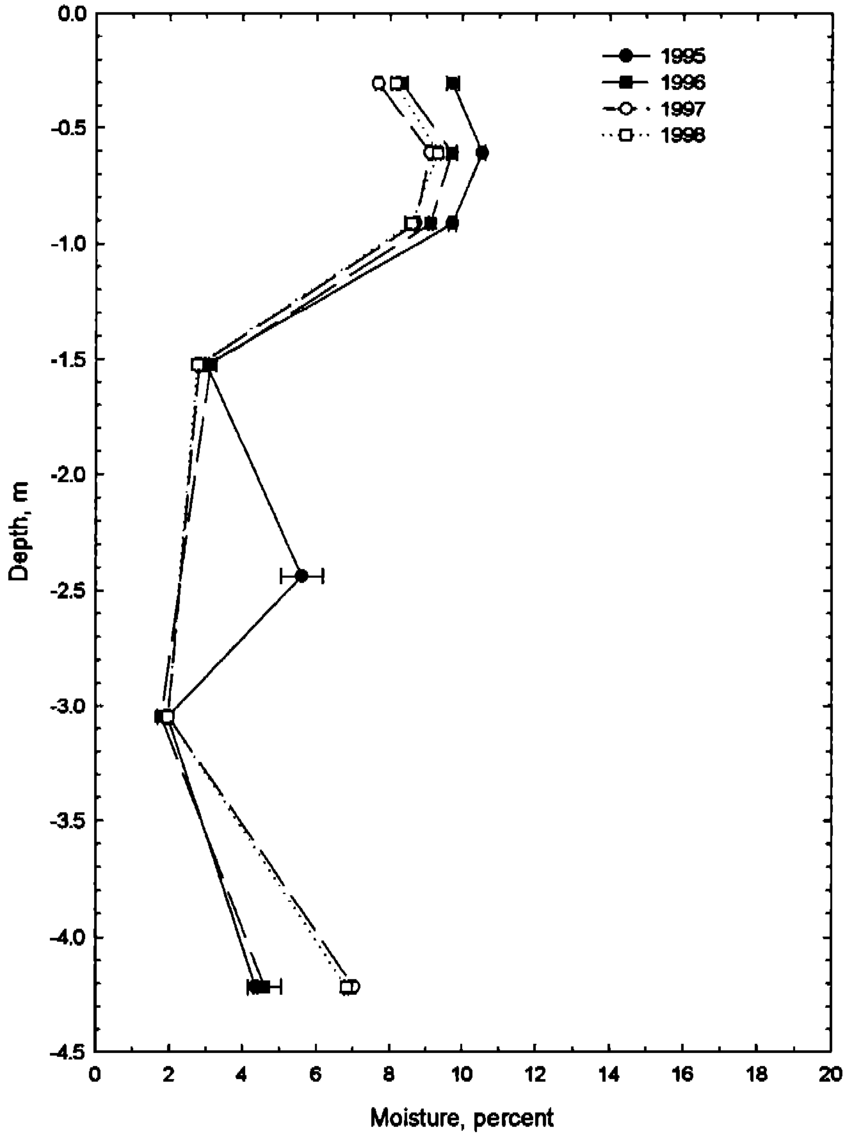

Figure 4-4. Moisture profile, control, Plot SE, Site 1

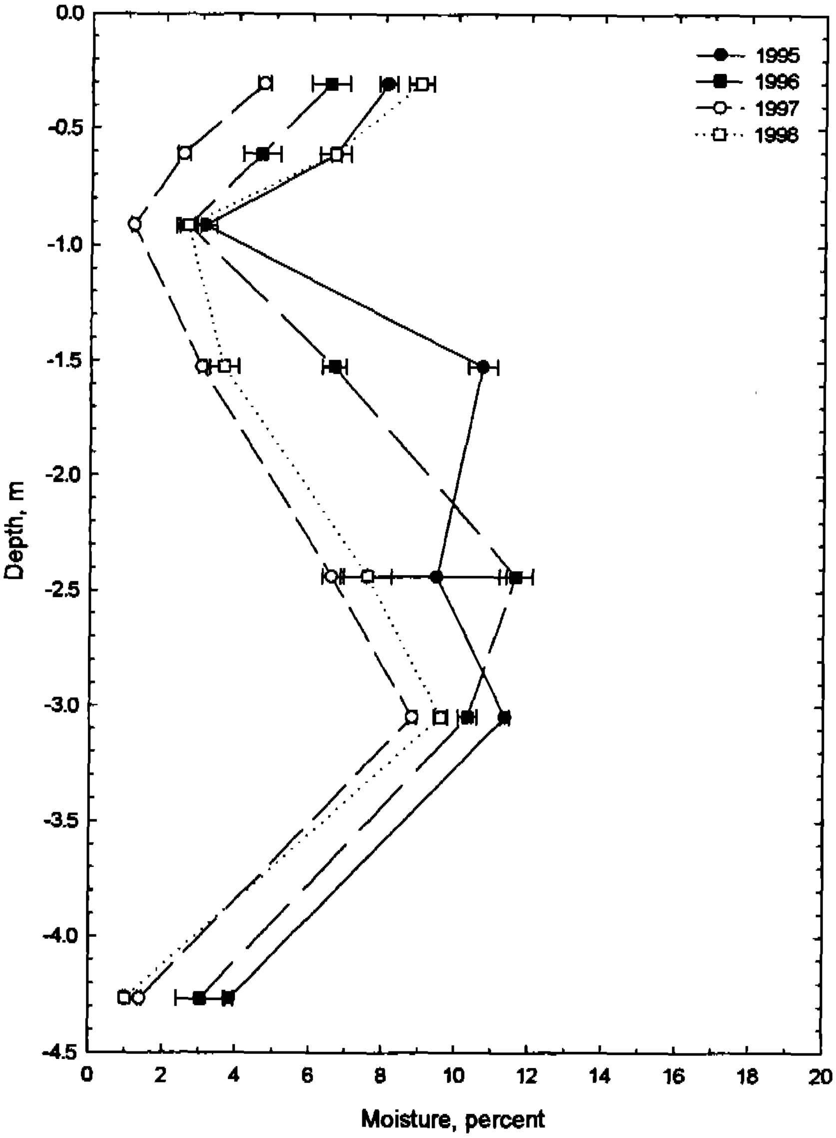

Figure 4-5. Moisture profile, control, Plot NW, Site 1

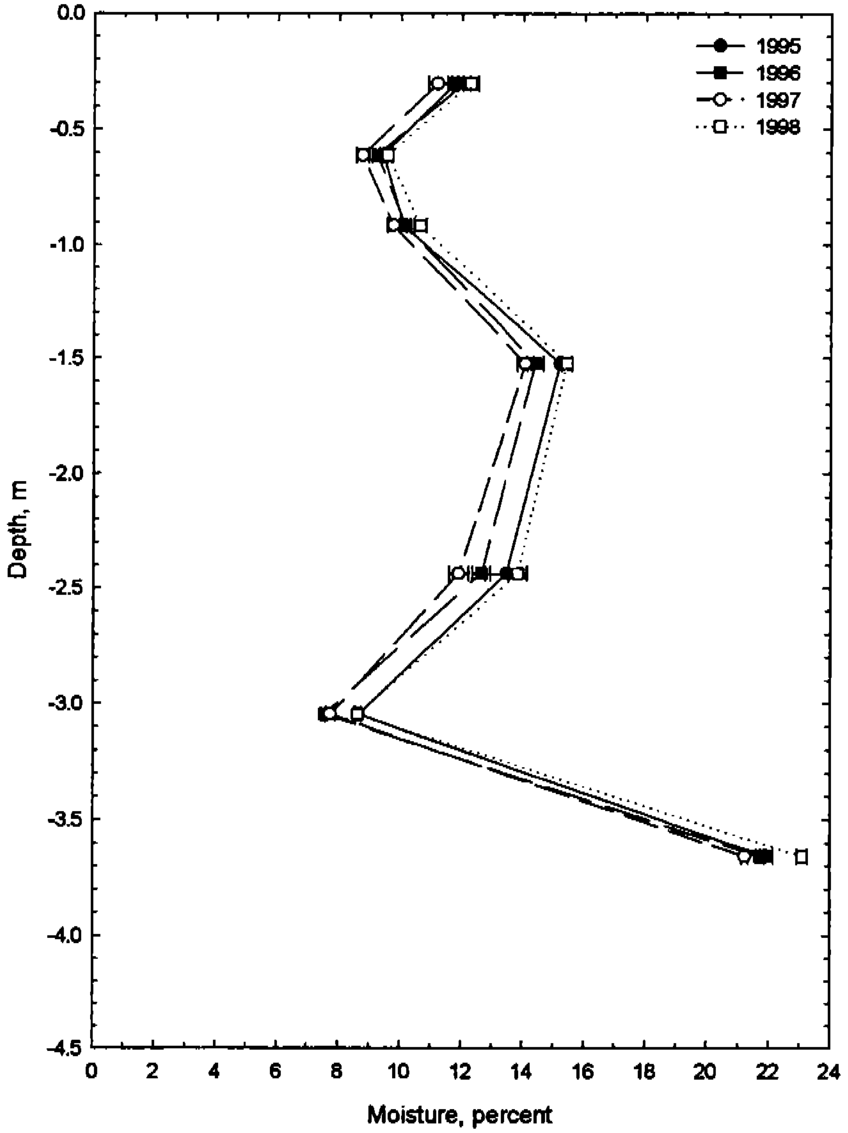

Figure 4-6. Moisture profile, *Atriplex*, Plot G, Site 2

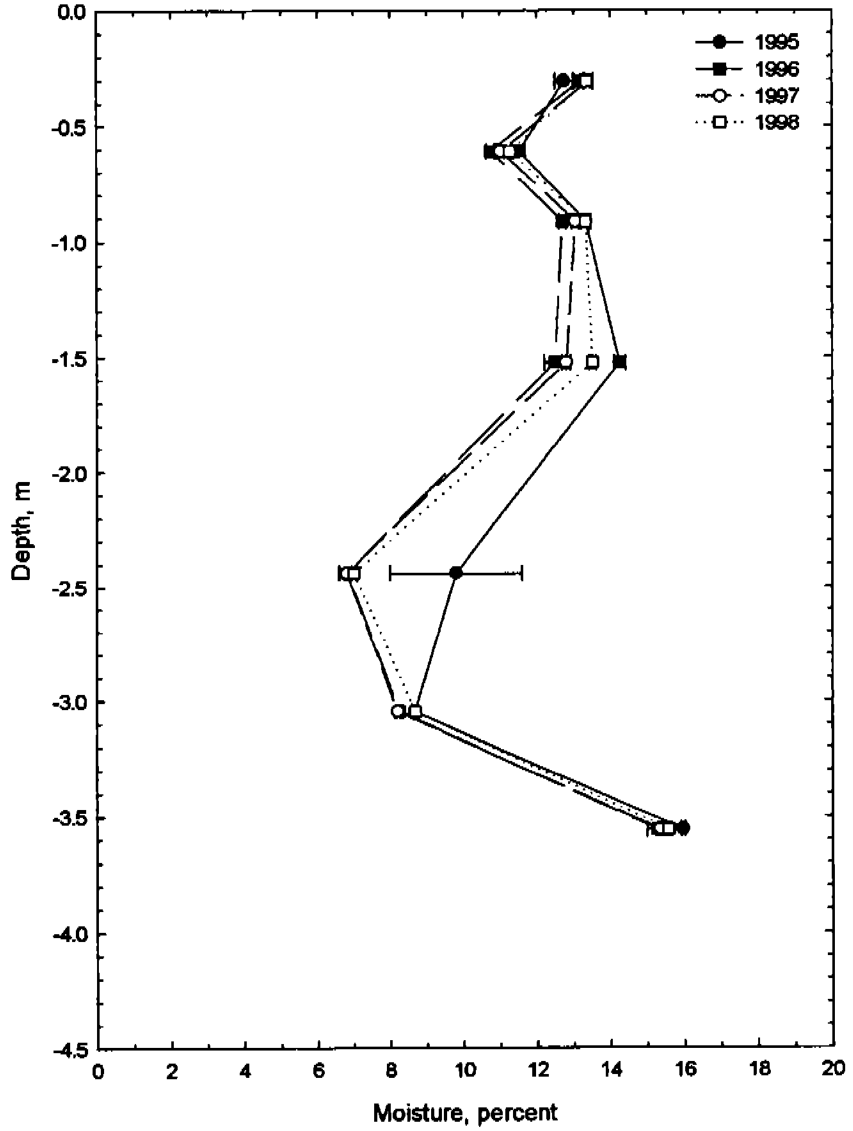

Figure 4-7. Moisture profile, *Paspalum*, Plot L, Site 2

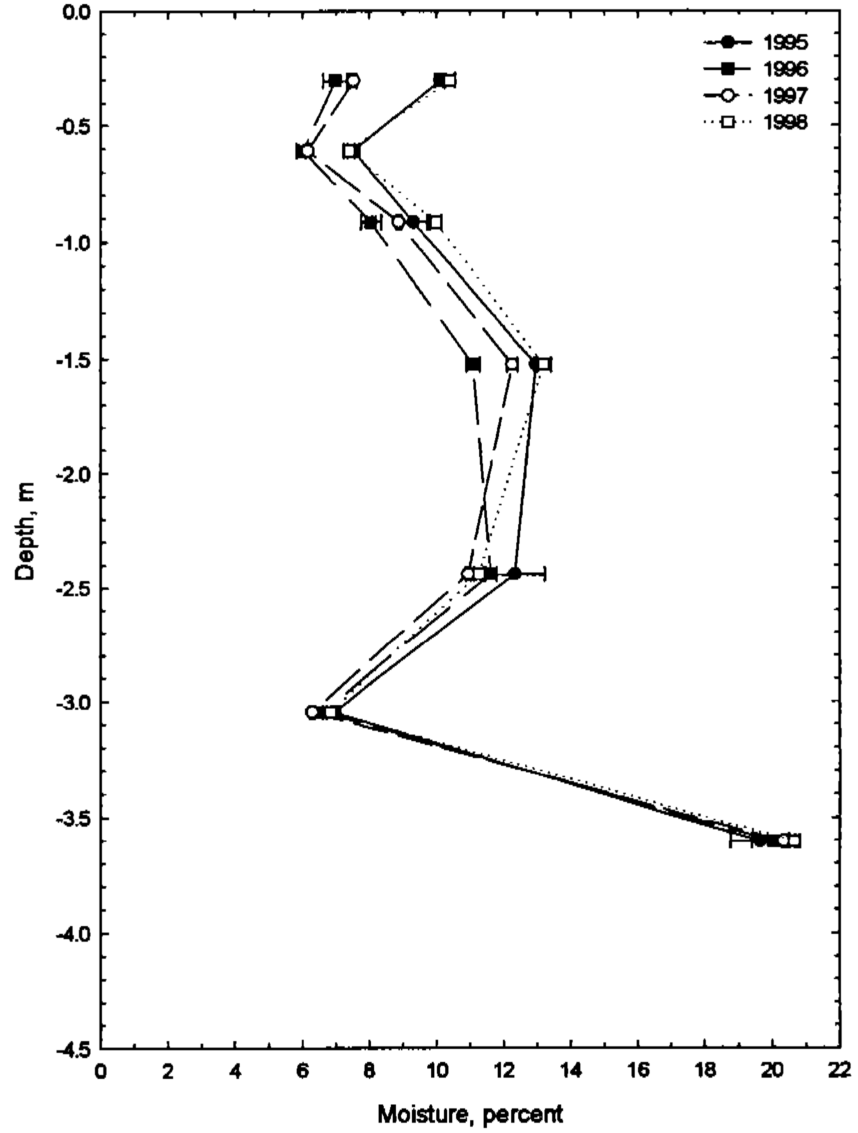

Figure 4-8. Moisture profile, control, Plot NW, Site2

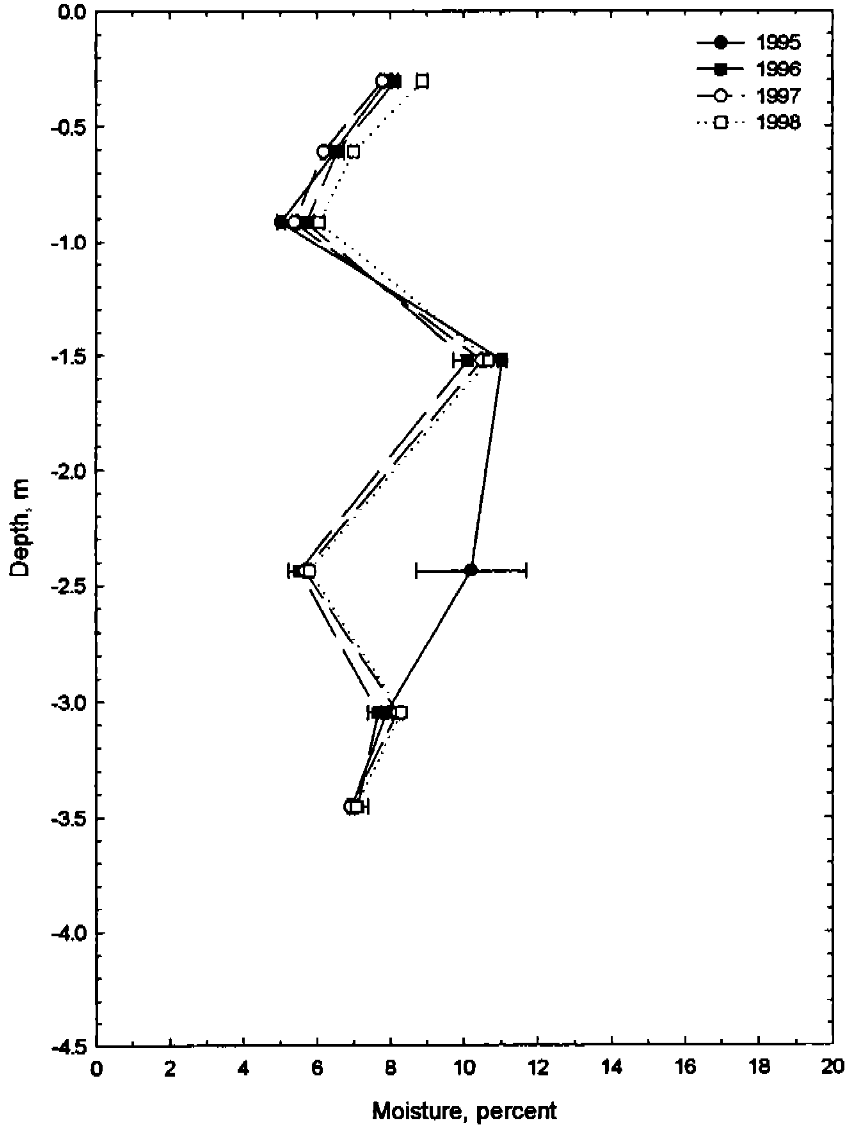

Figure 4-9. Moisture profile, control, Plot SE, Site 2

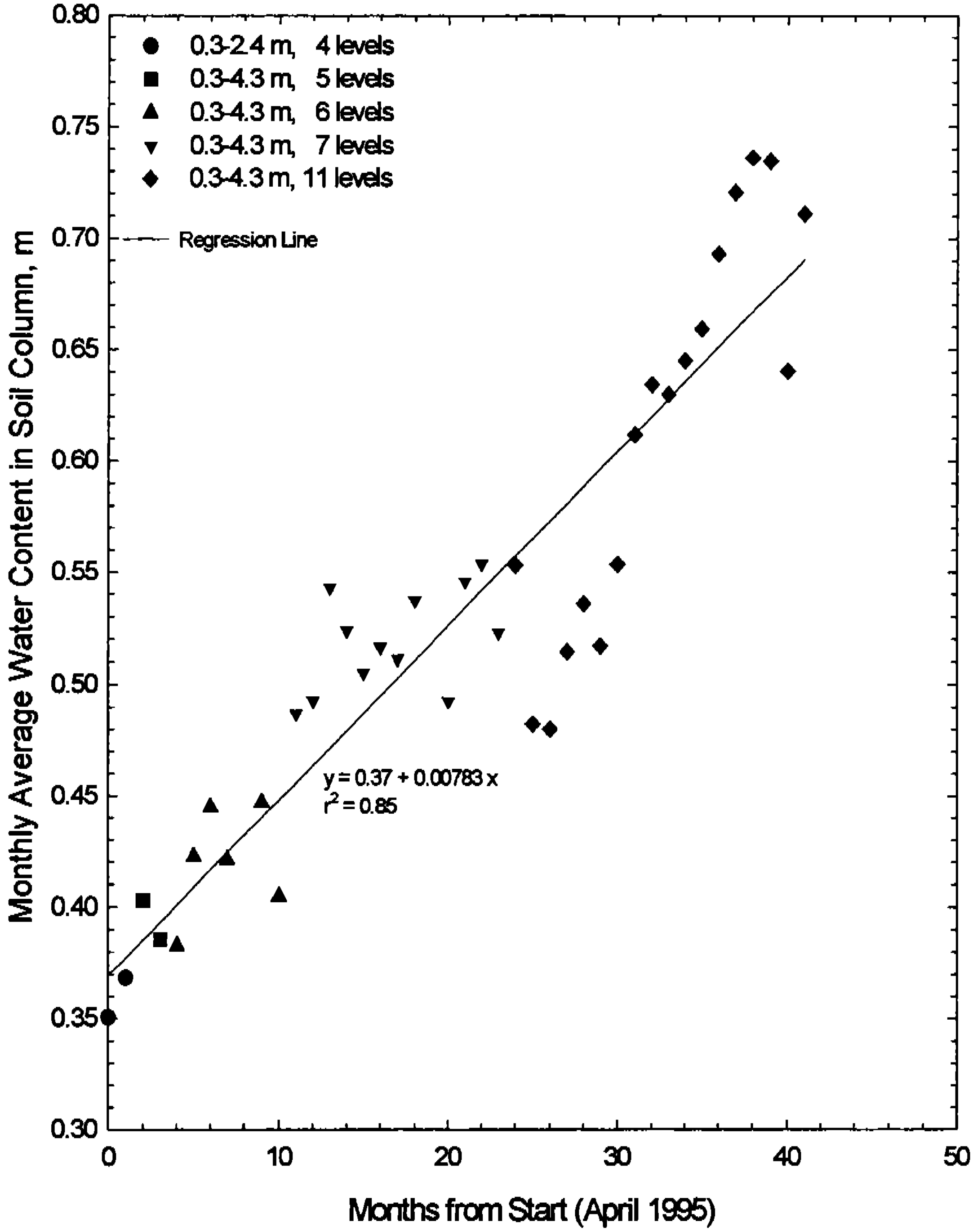

Figure 4-10. Total water content of soil column, *Atriplex*, Plot A, Site 1

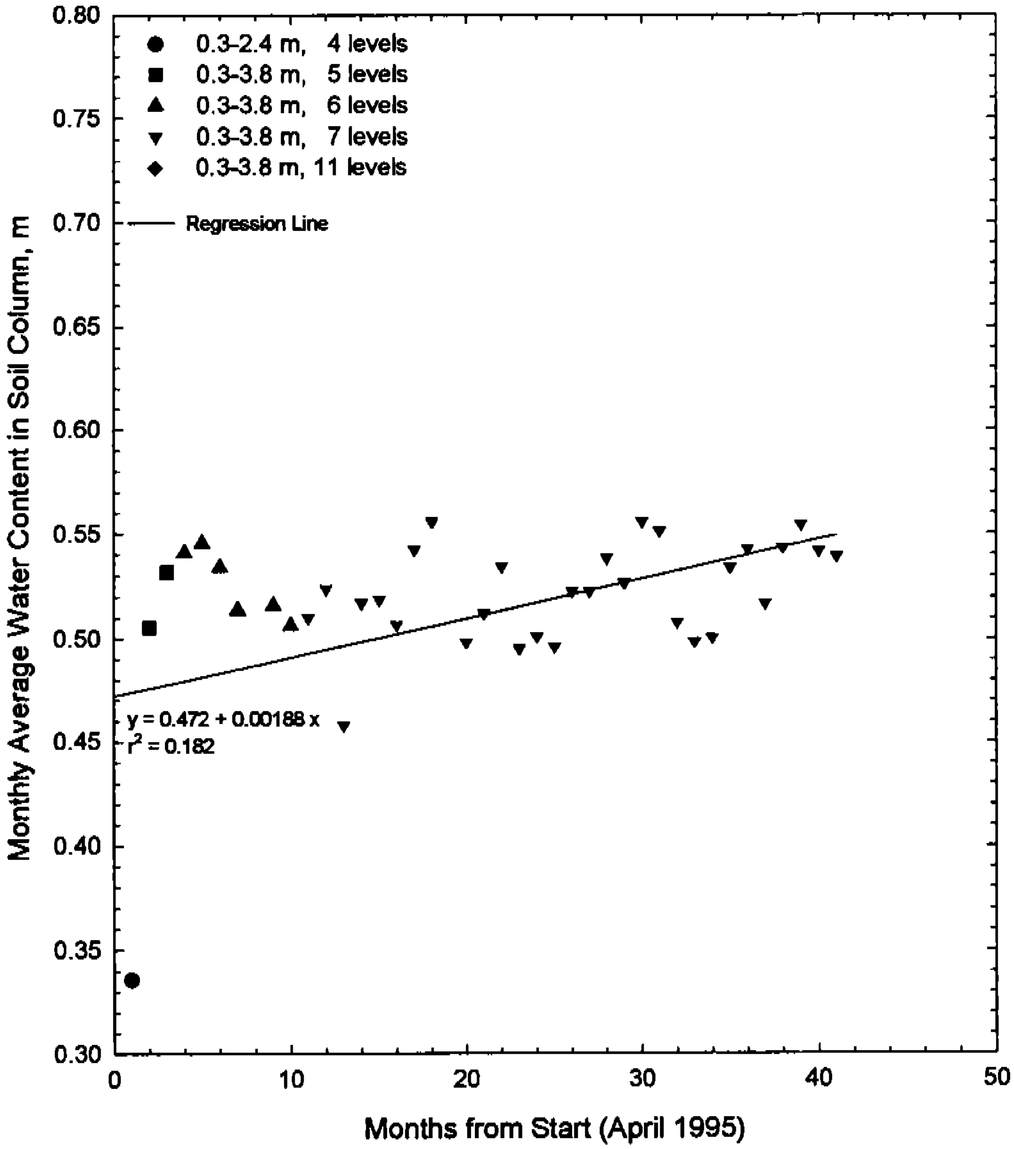

Figure 4-11. Total water content of soil column, *Paspalum*, Plot F, Site 1

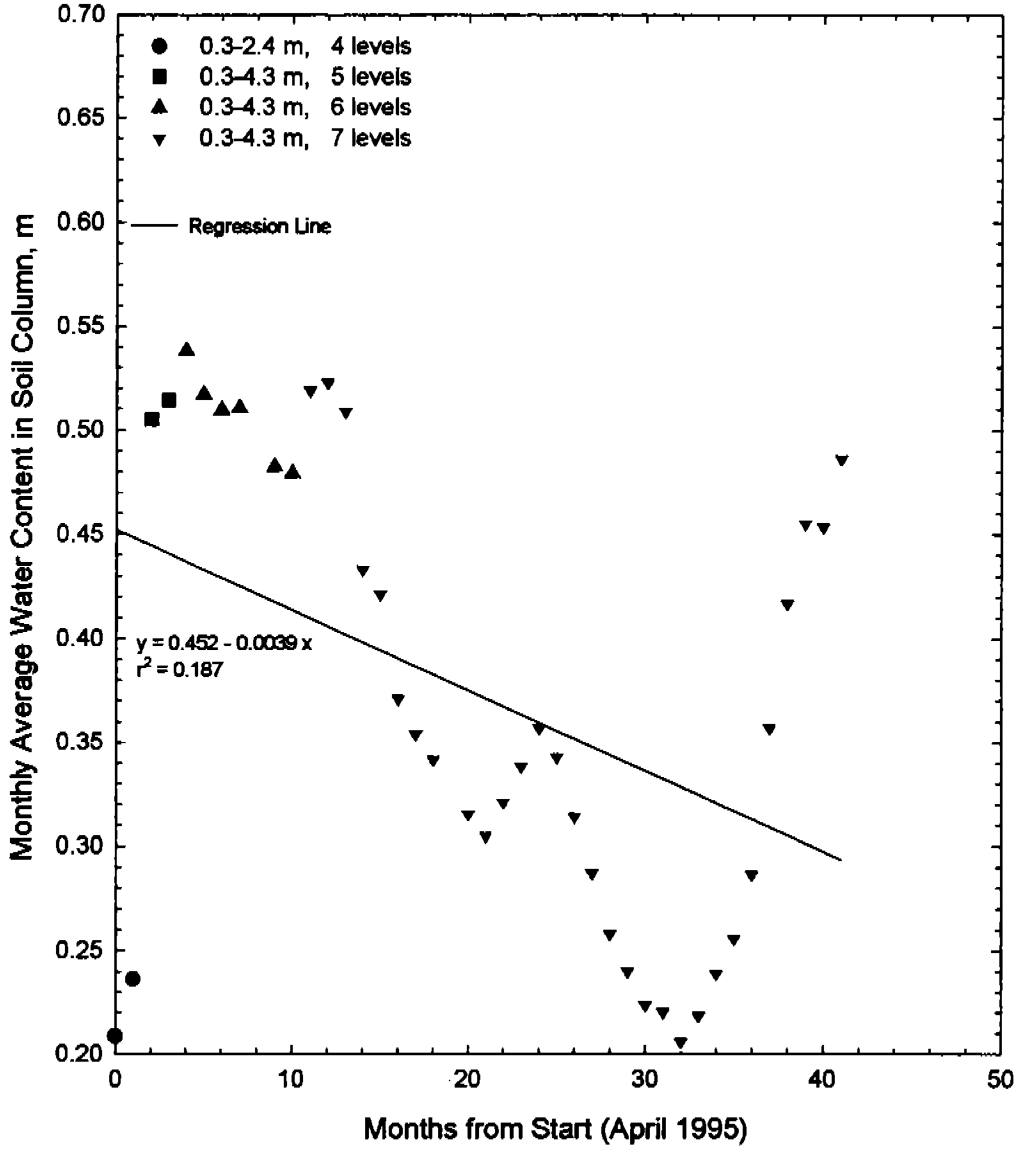

Figure 4-12. Total water content of soil column, control, Plot NW, Site 1

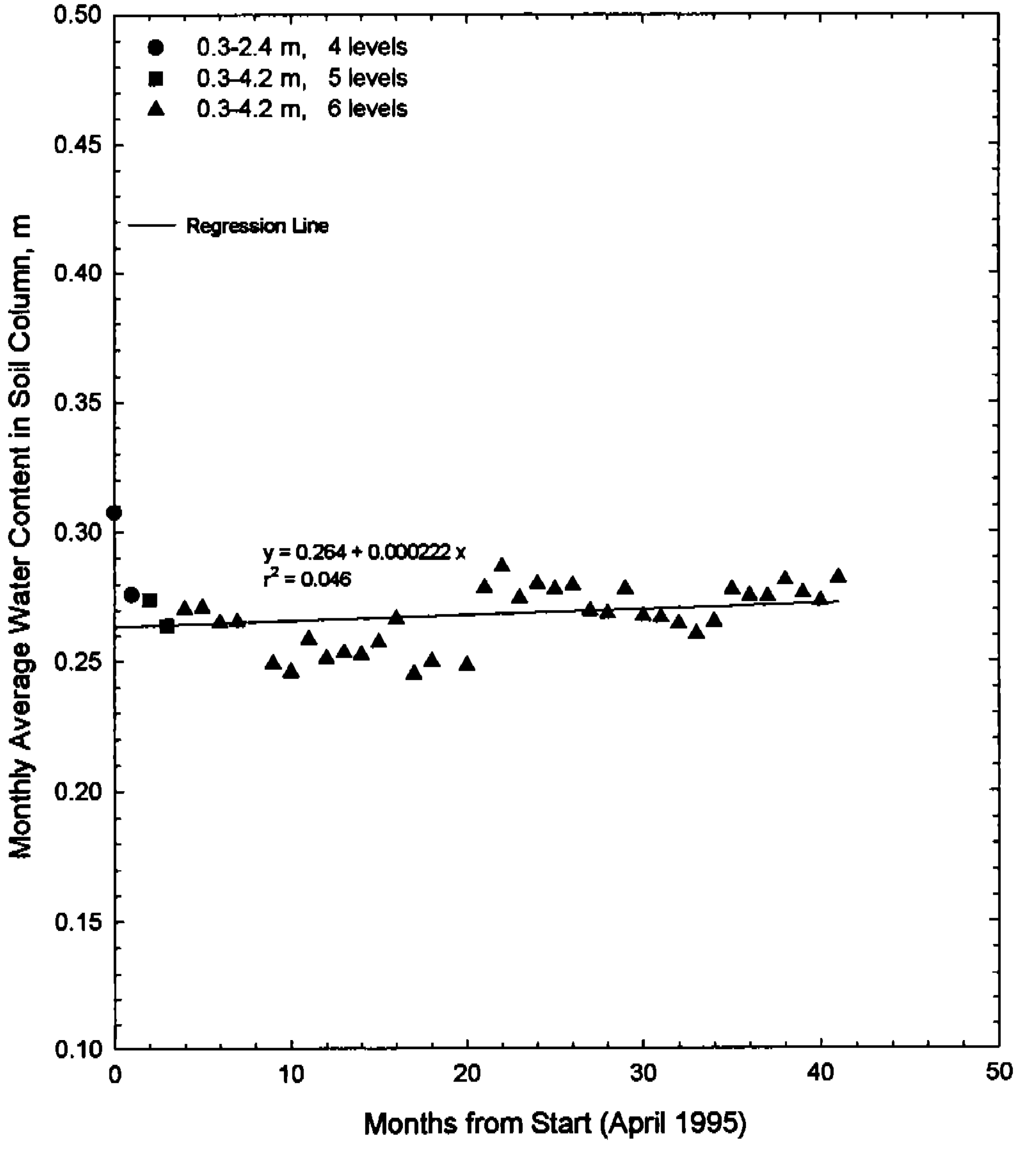

Figure 4-13. Total water content of soil column, control, Plot SE, Site 1

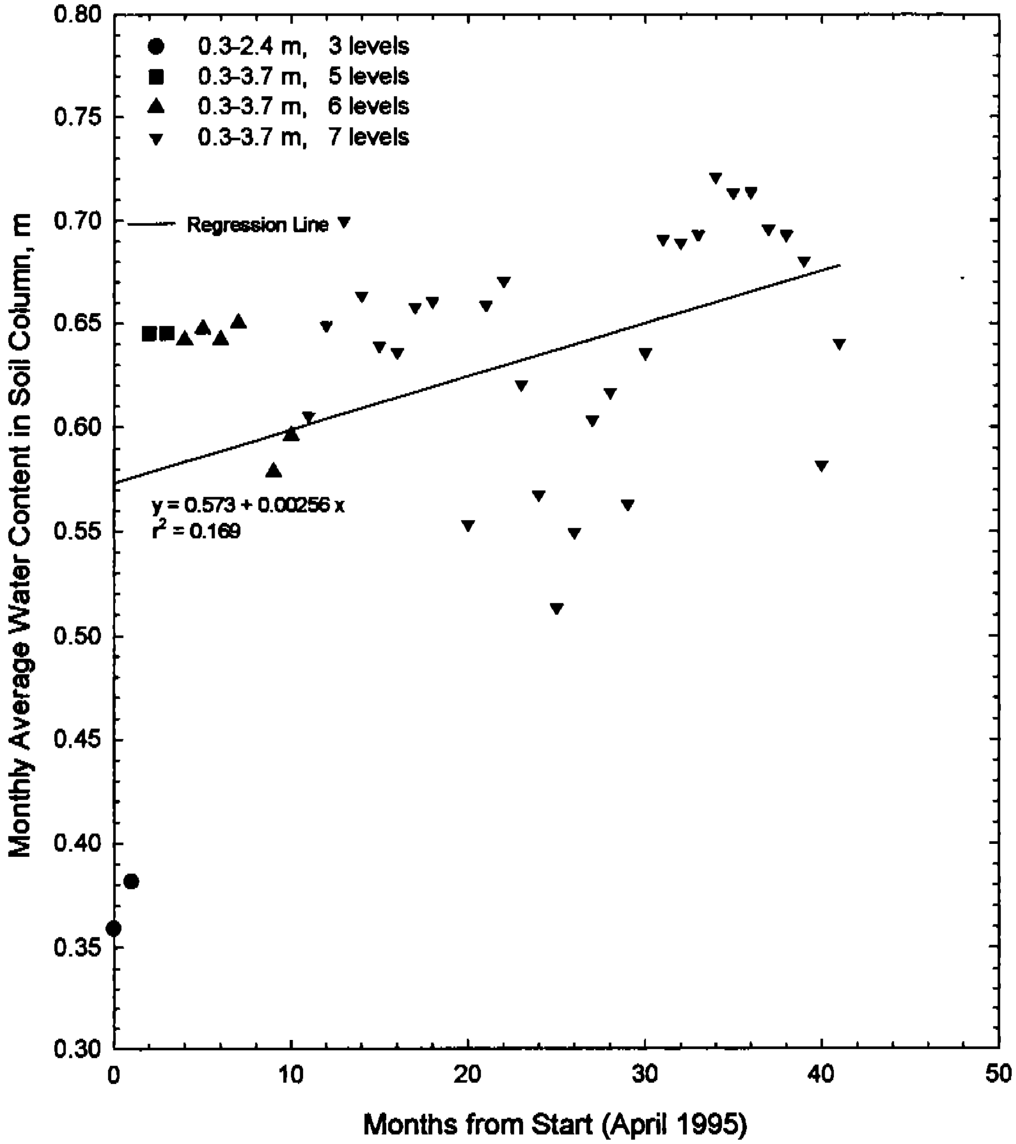

Figure 4-14. Total water content of soil column, *Atriplex*, Plot G, Site 2

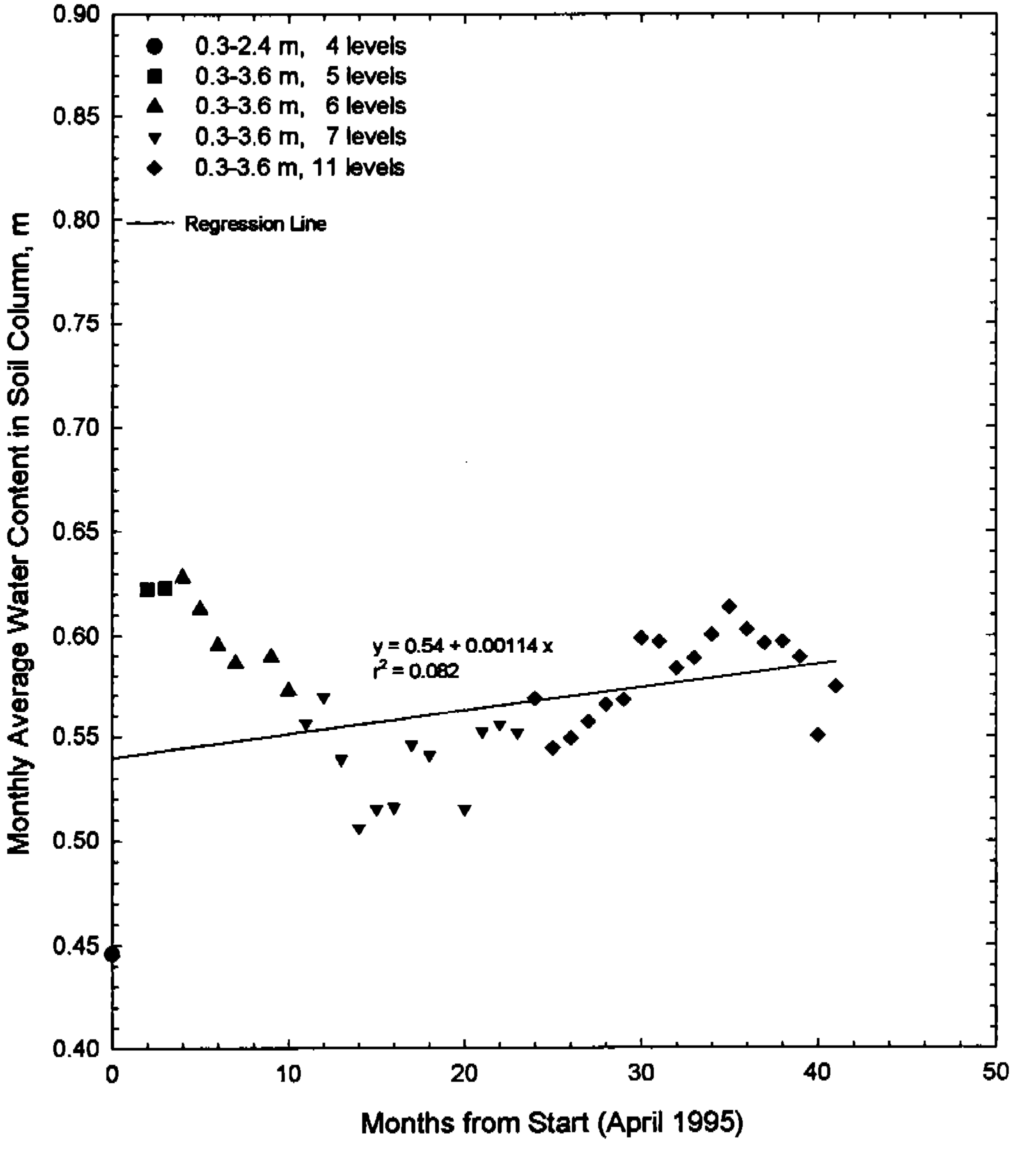

Figure 4-15. Total water content of soil column, *Paspalum*, Plot L, Site 2

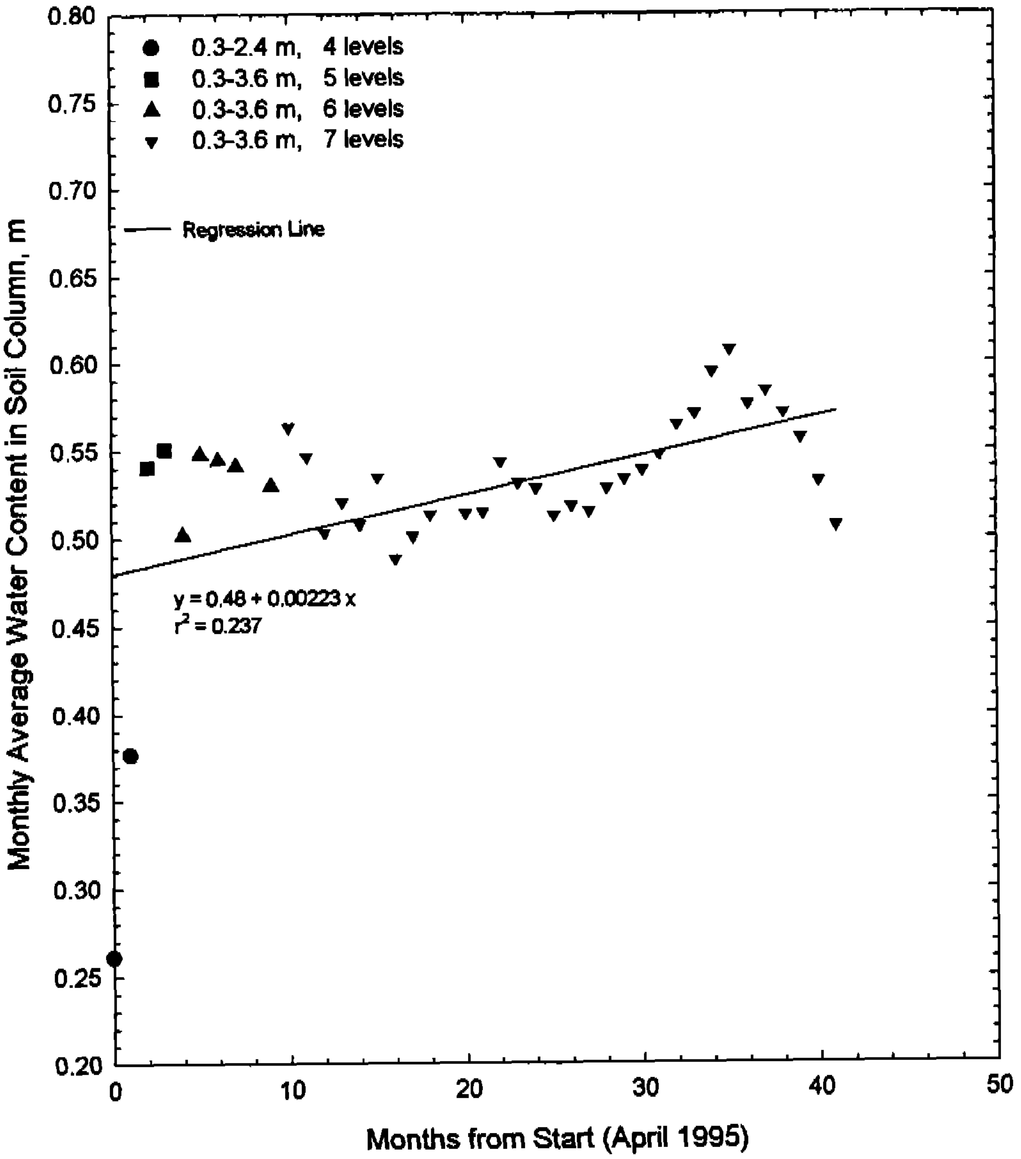

Figure 4-16. Total water content of soil column, control, Plot NW, Site 2

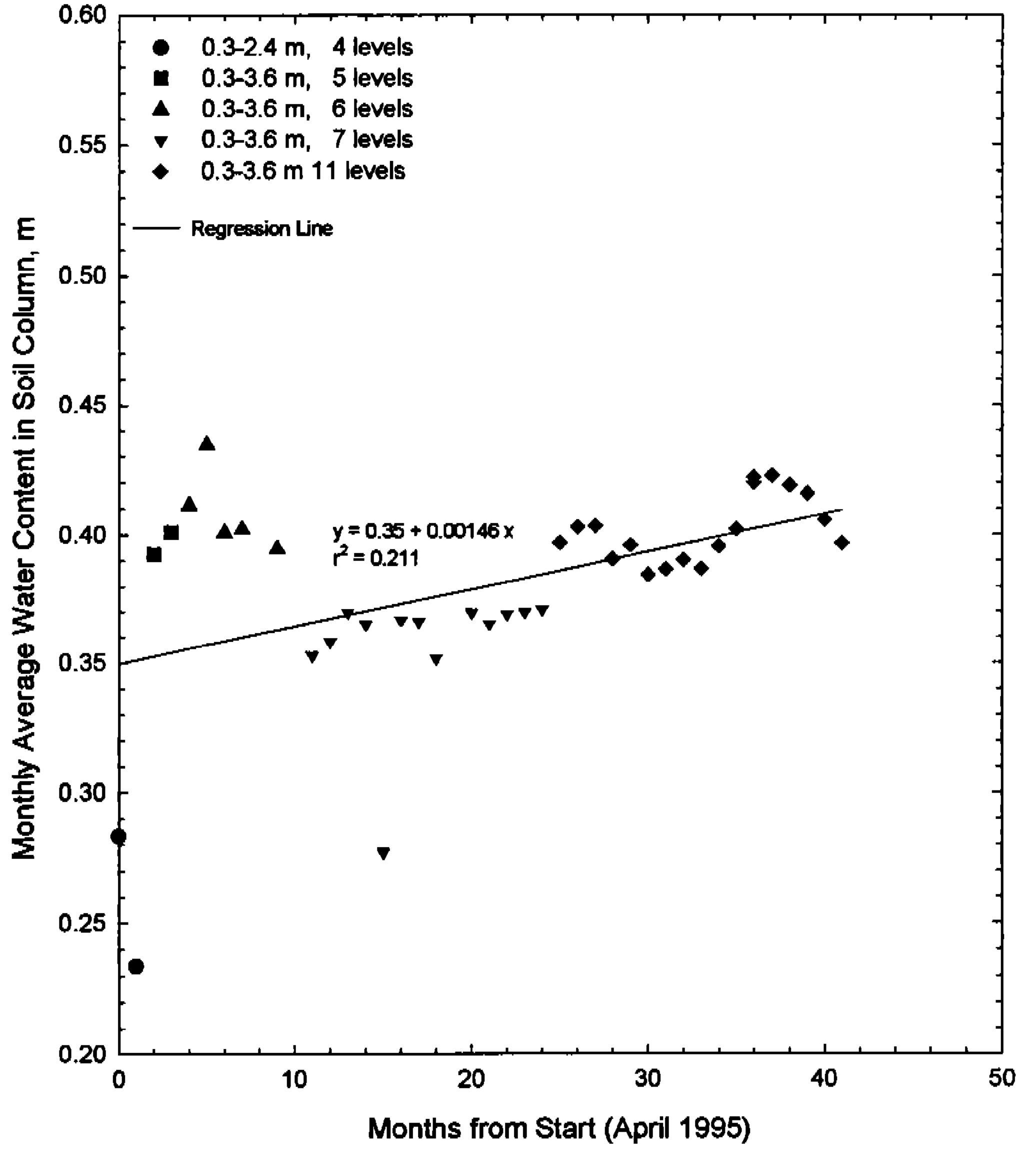

Figure 4-17. Total water content of soil column, control, Plot SE, Site 2

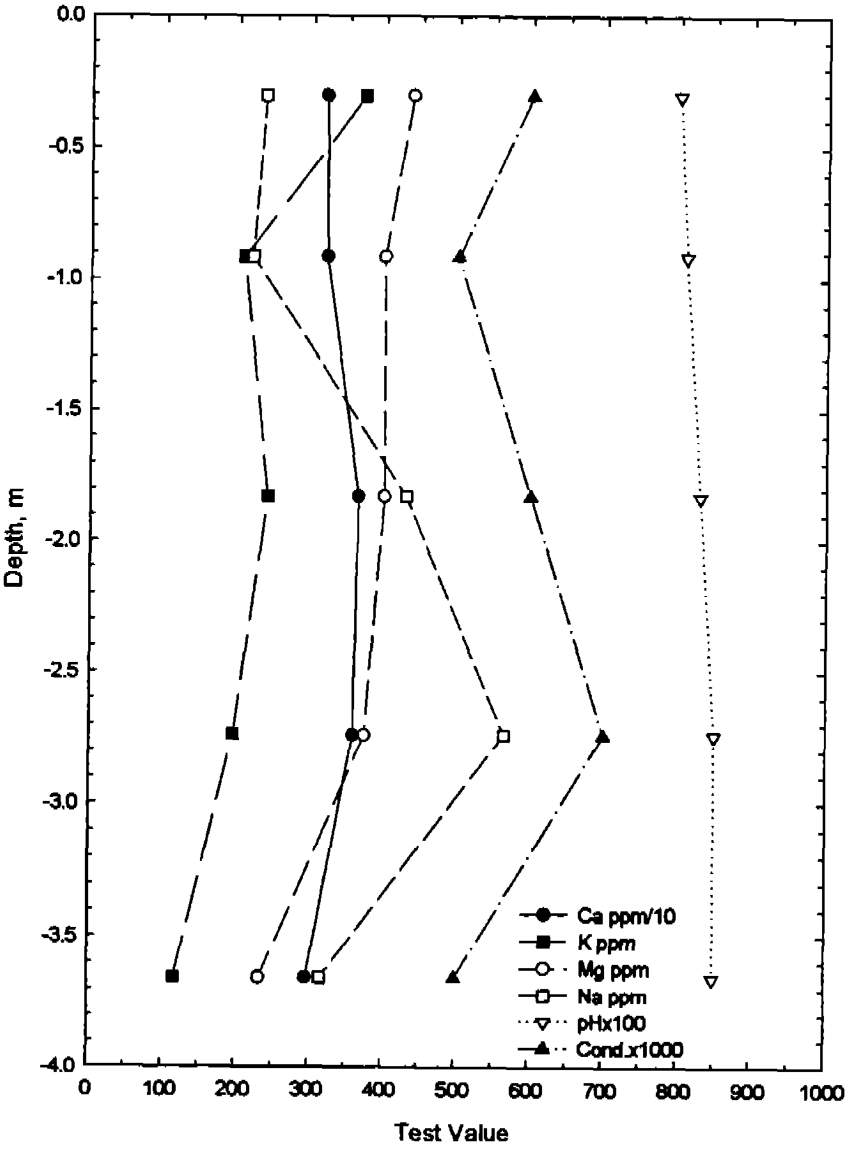

Figure 4-18. Chemical profile, *Atriplex*, Plot A, Site 1, 1998

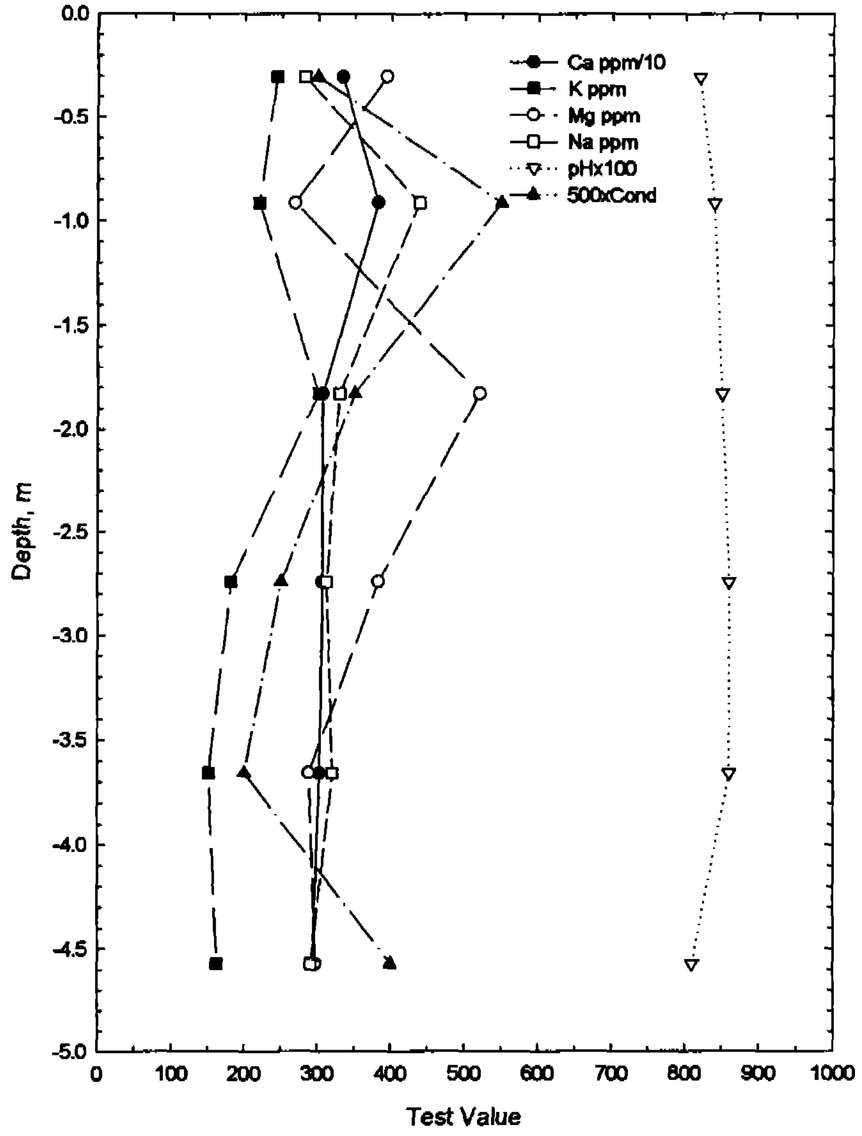

Figure 4-19. Chemical profile, *Paspalum*, Plot F, Site 1, 1998

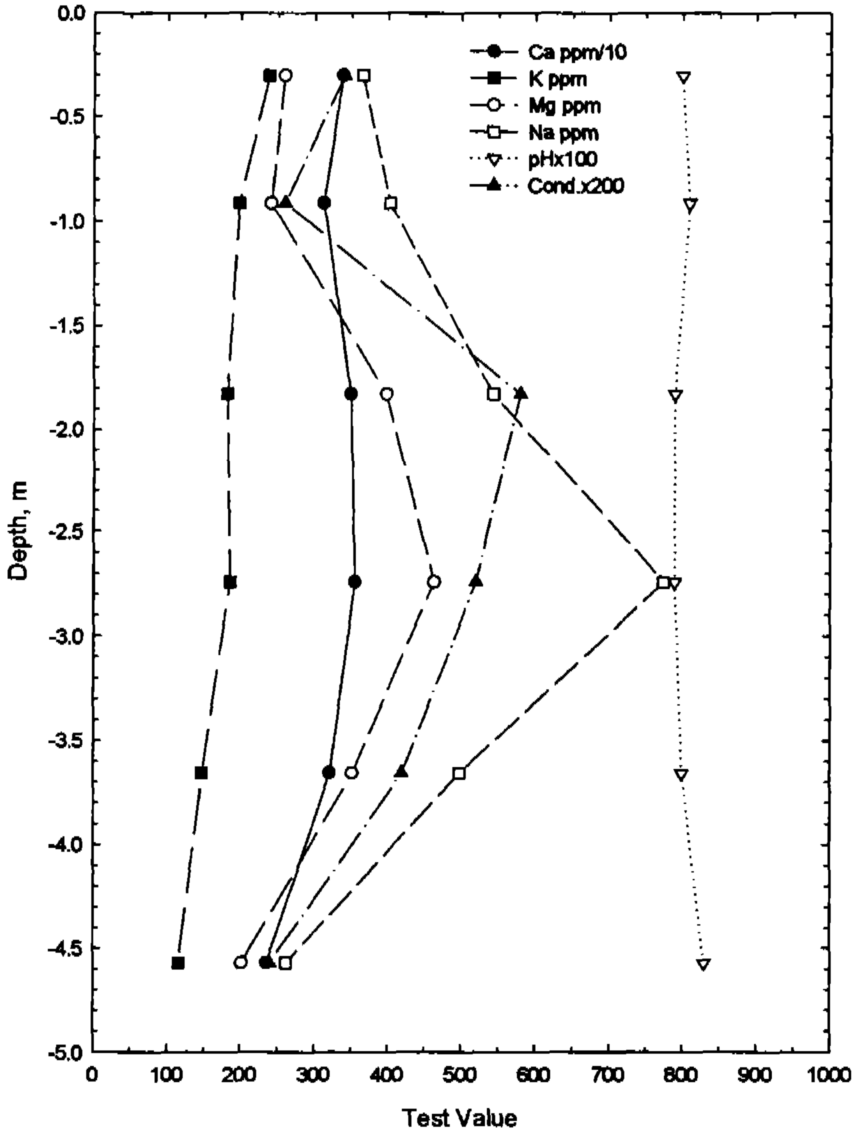

Figure 4-20. Chemical profile, control, Plot NW, Site 1, 1998

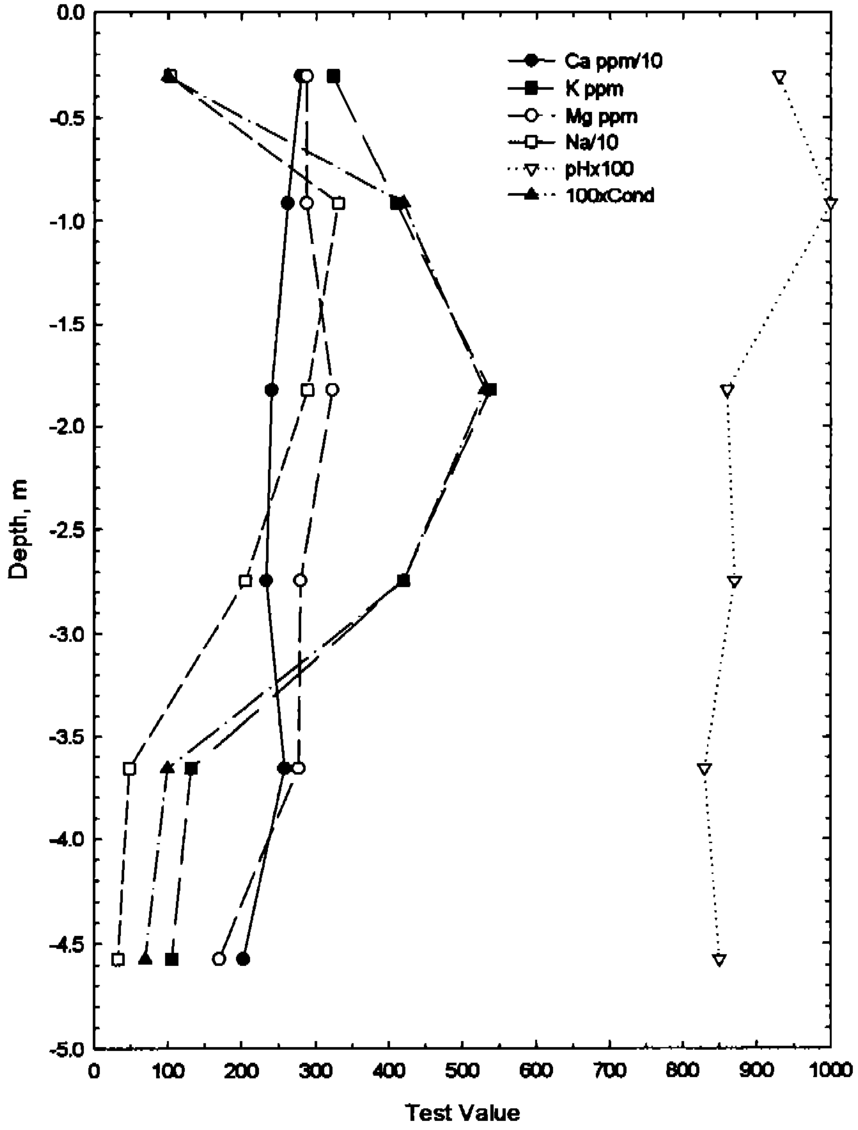

Figure 4-21. Chemical profile, control, Plot SE, Site 1, 1998

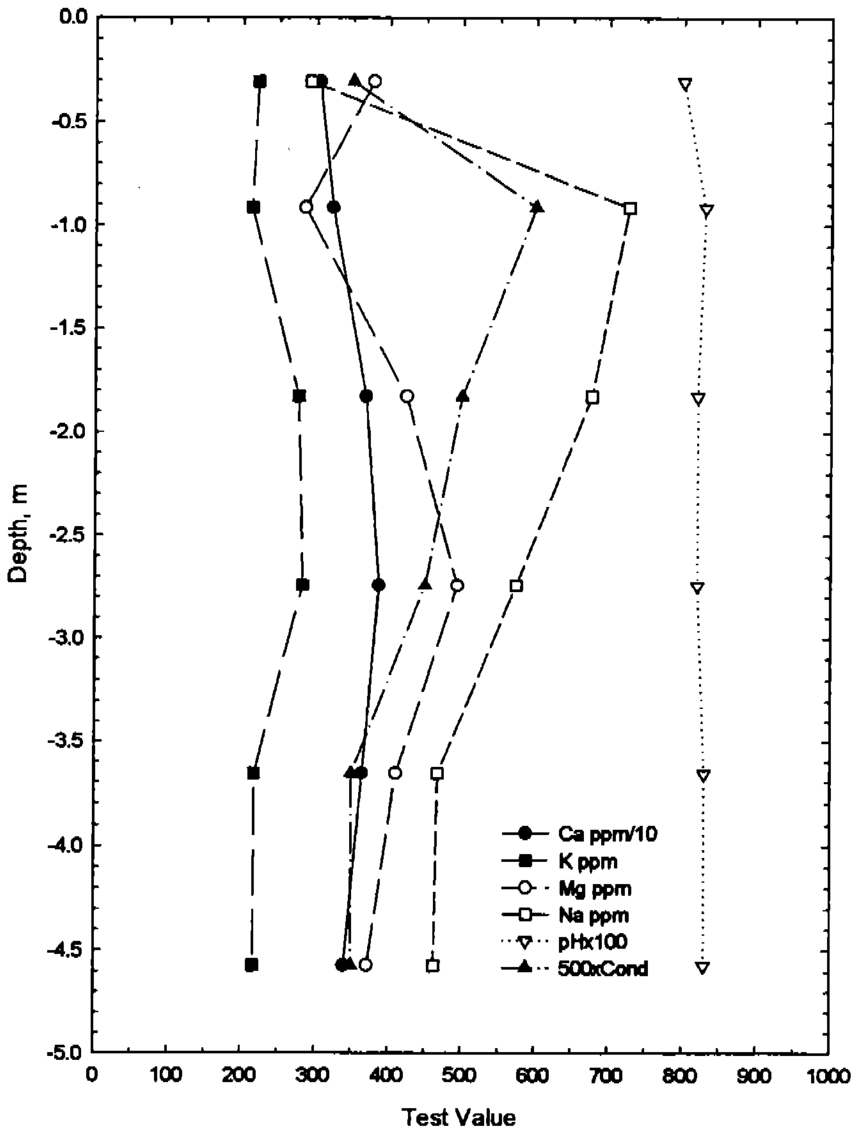

Figure 4-22. Chemical profile, *Atriplex*, Plot G, Site 2, 1998

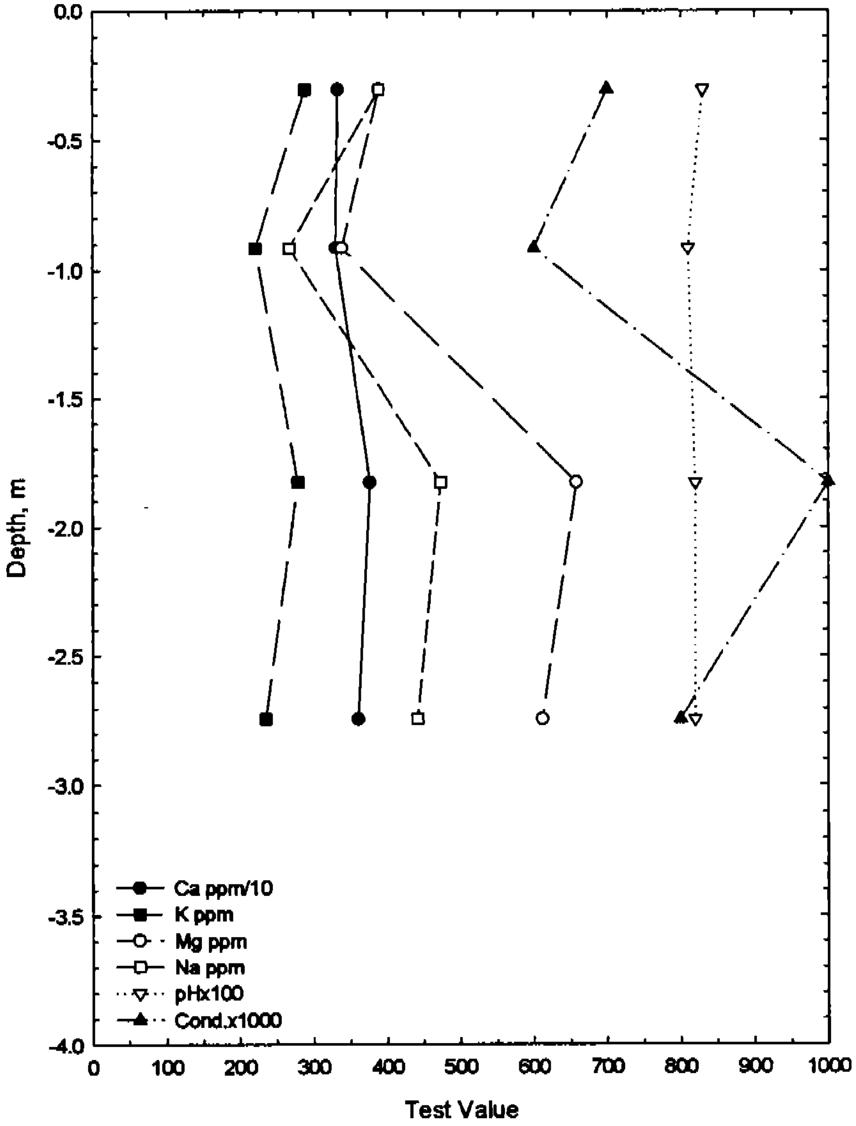

Figure 4-23. Chemical profile, *Paspalum*, Plot L, Site 2, 1998

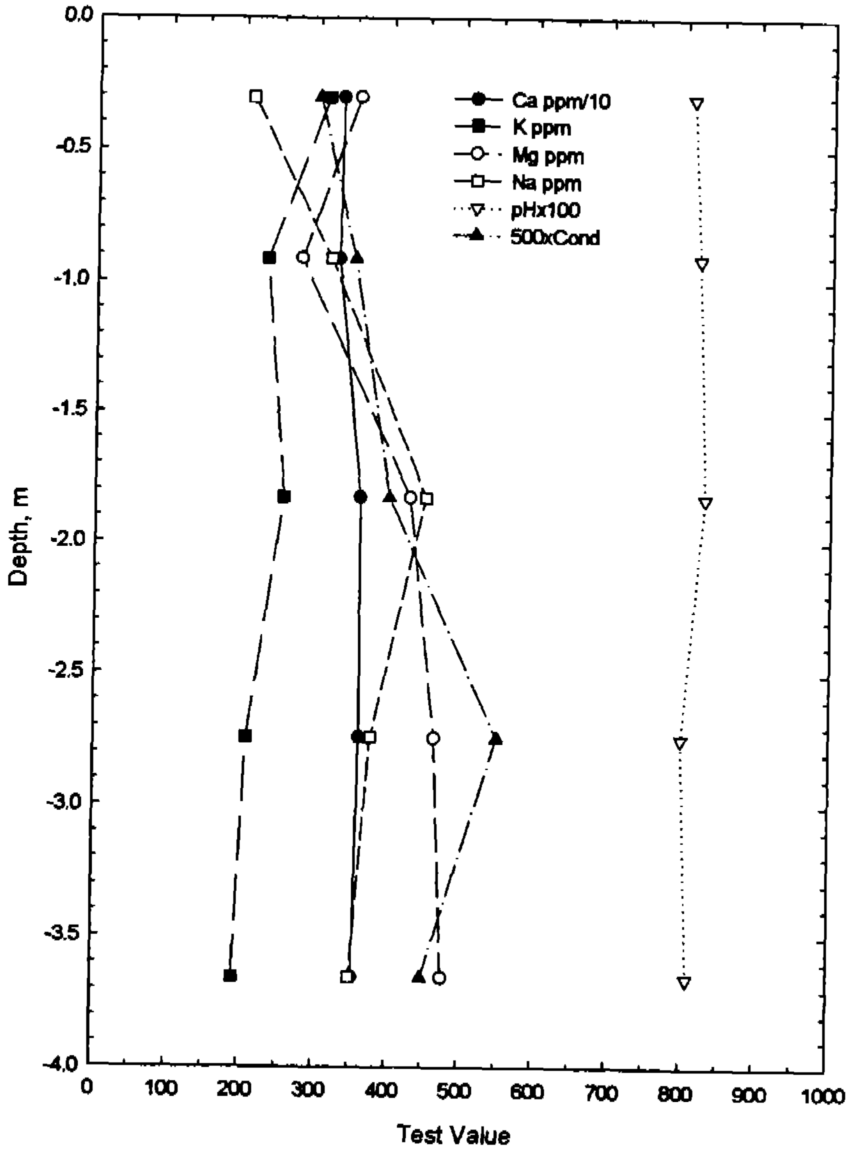

Figure 4-24. Chemical profile, control, Plot NW, Site 2, 1998

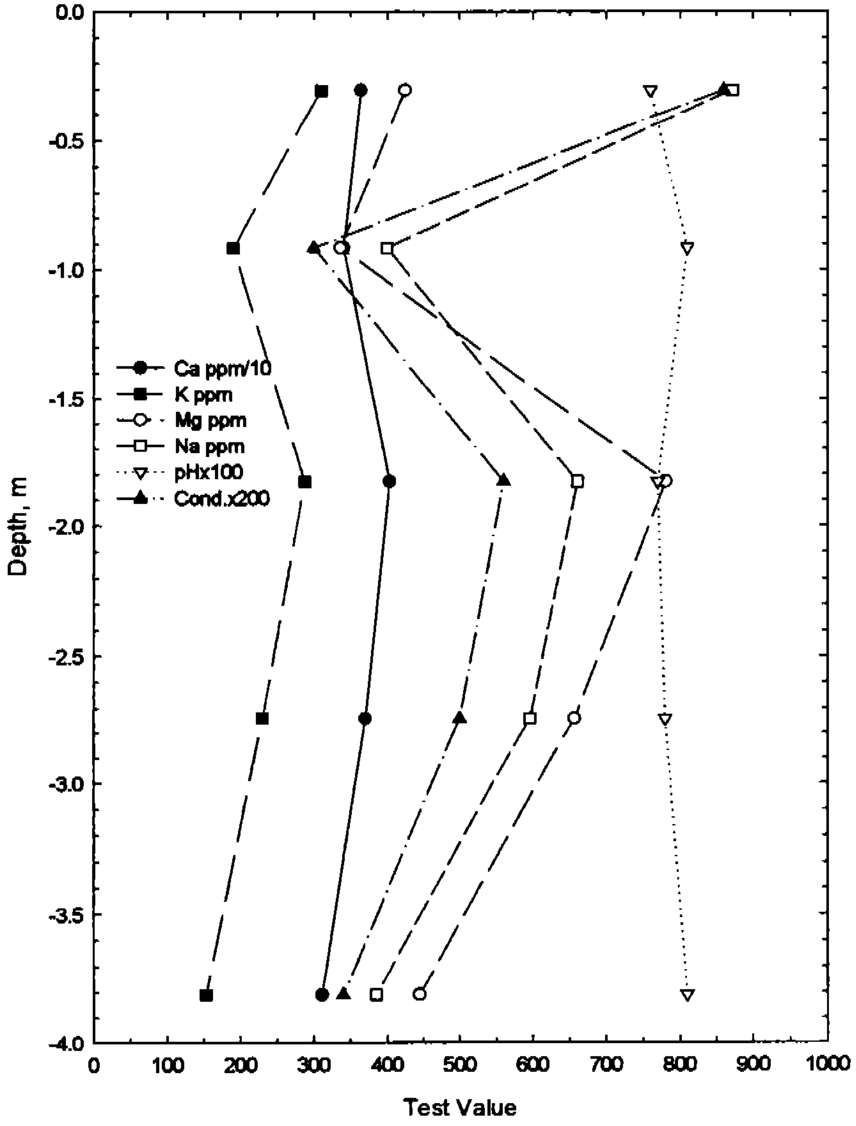

Figure 4-25. Chemical profile, control, Plot SE, Site 2, 1998

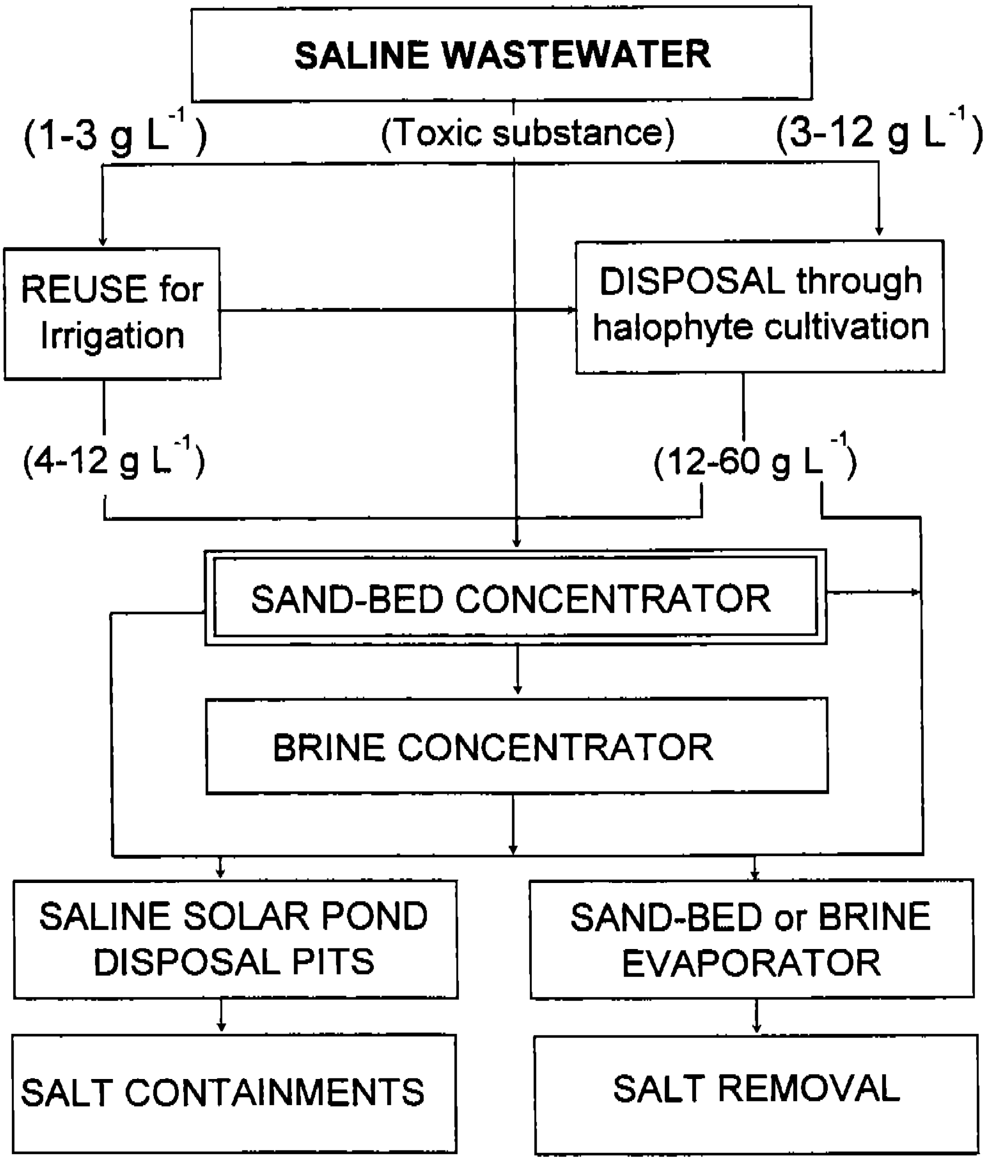

Figure 5-1. Saline wastewater handling options; excluding evaporation ponds and deep-well injection.

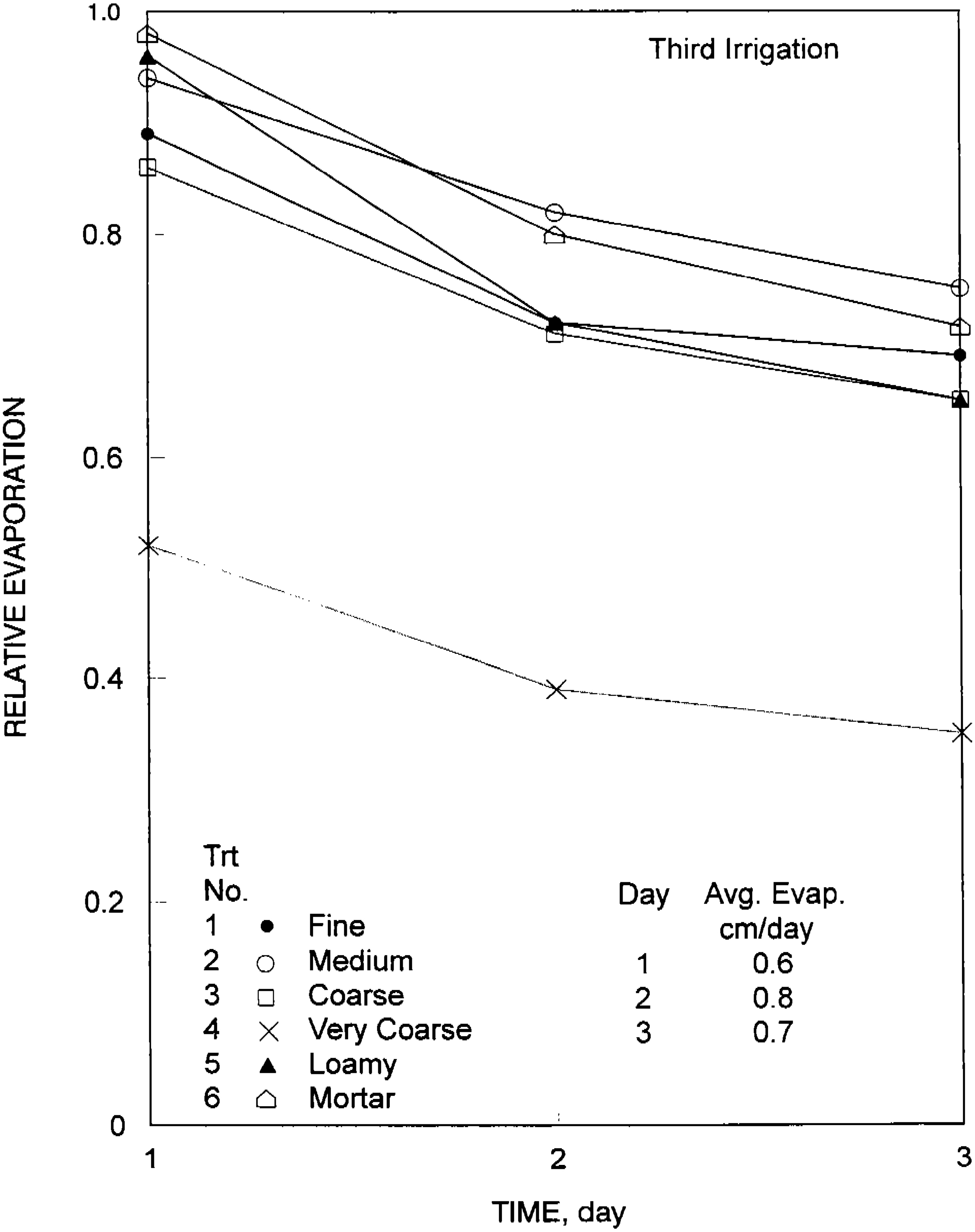

Figure 7-1. The daily water evaporation from the sand-beds consisting of various fractions.

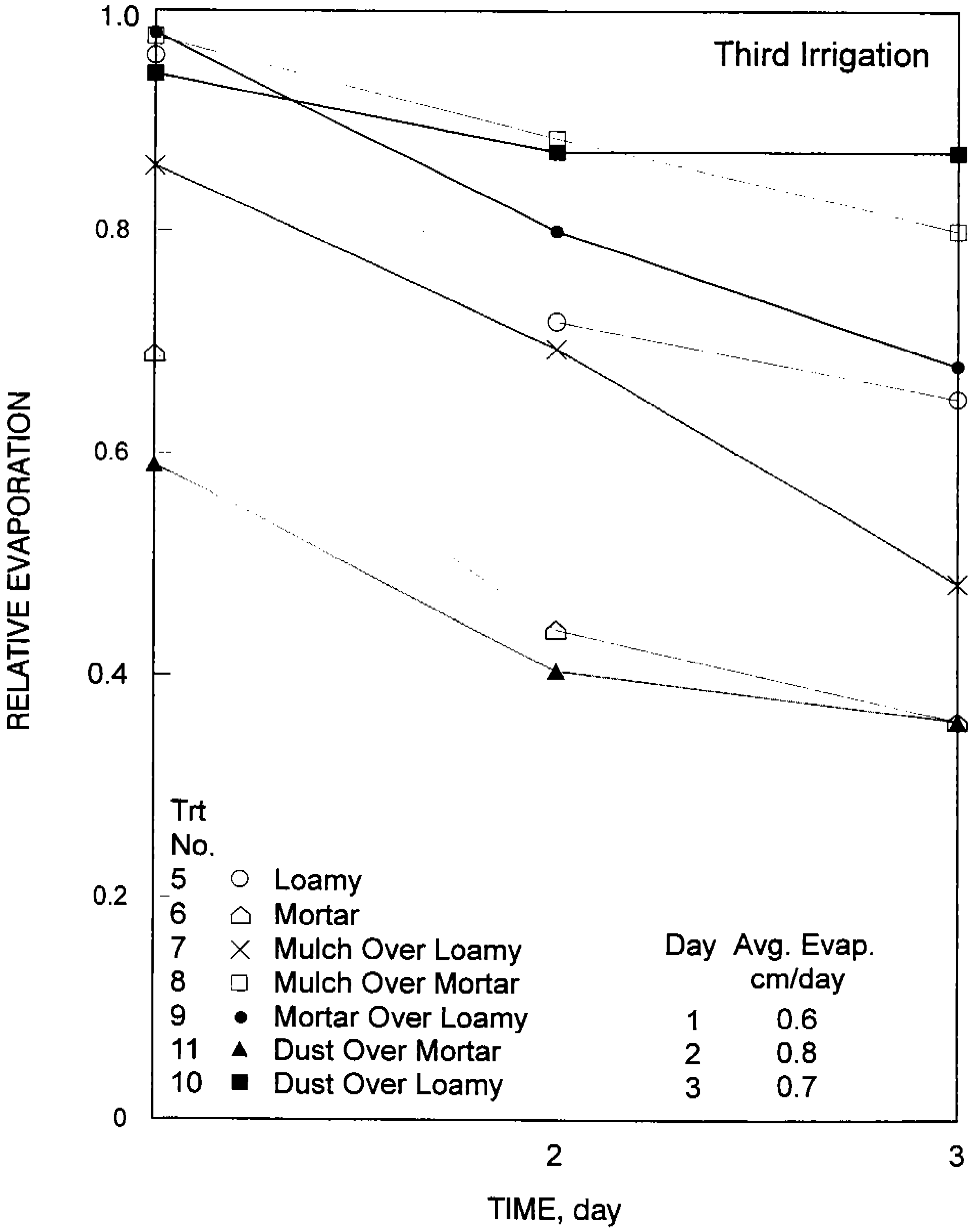

Figure 7-2. The daily water evaporation from the sand-beds with various layering configurations.

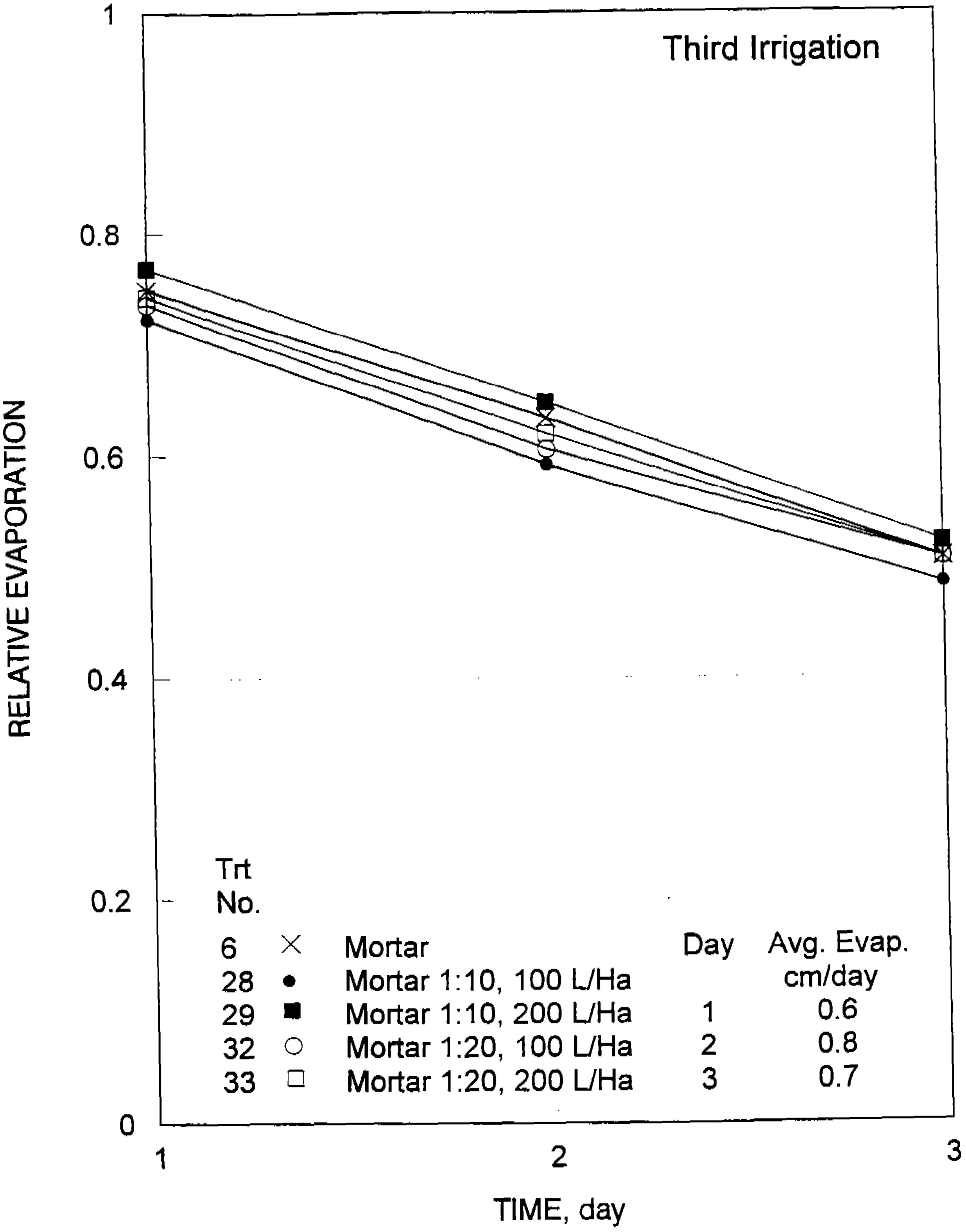

Figure 7-3. The daily water evaporation from the sand-beds (mortar sand) as affected by stabilizer application.

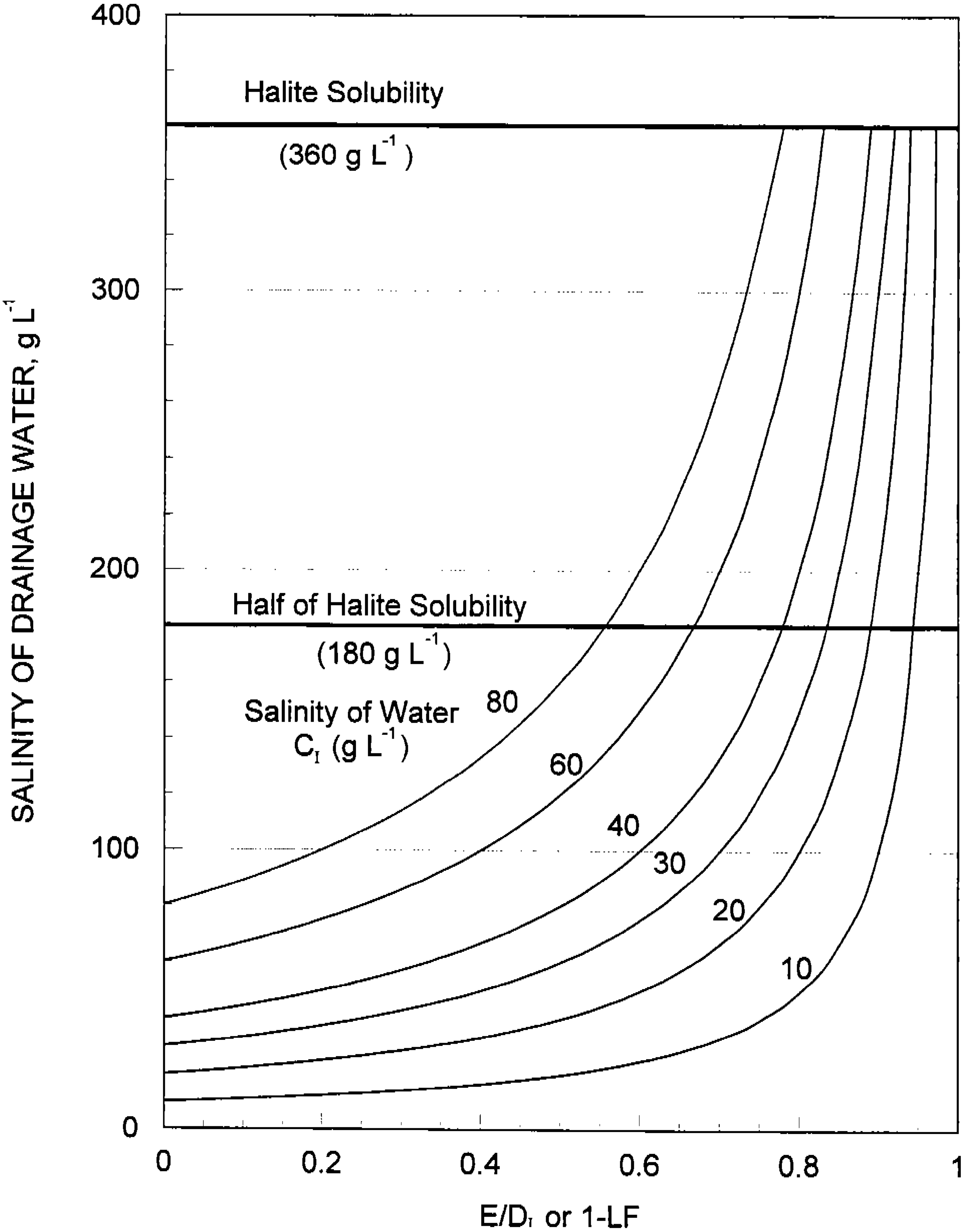

Figure 8-1. The theoretical relationship between salinity of irrigation water and salinity of drainage water.

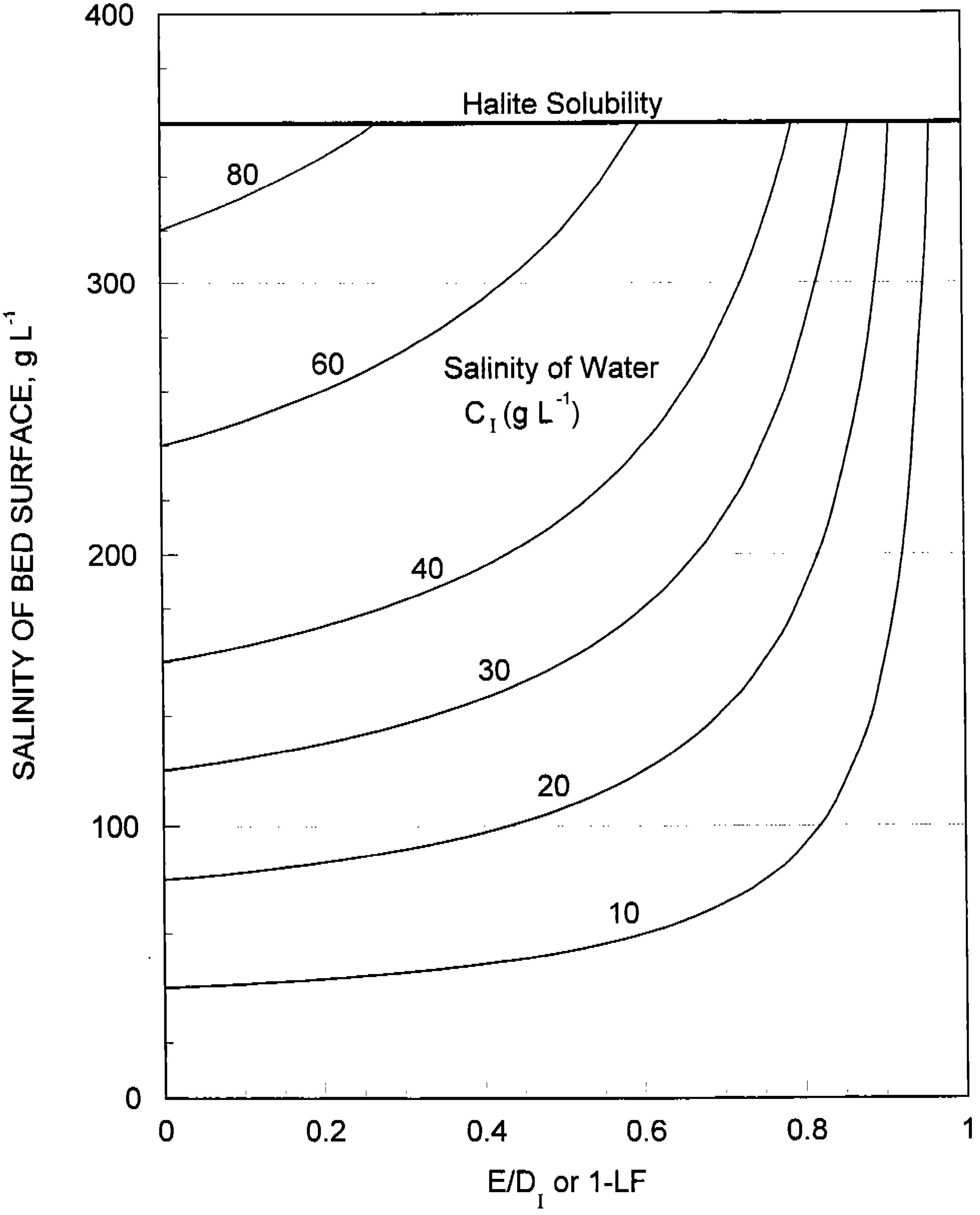

Figure 8-2. Estimated salinity of the bed surface when saline solutions are concentrated to various evaporated fractions (E/D_I) or the leaching fraction (LF).

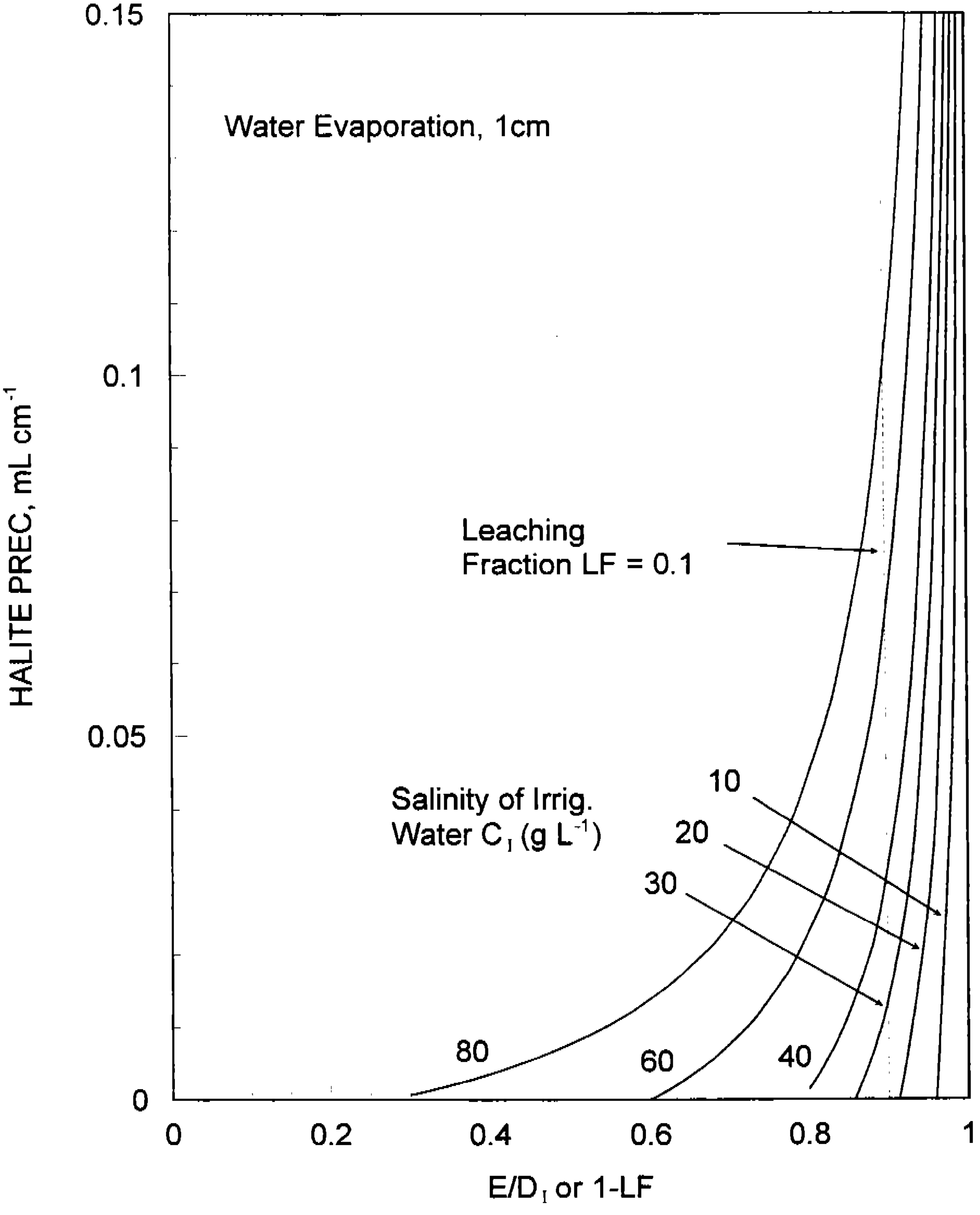

Figure 8-3. Estimated quantities of salts (NaCl) which may accumulate in the surface of sand-beds as related to salinity of saline water (C_I) and the evaporated fraction (E/D_I).

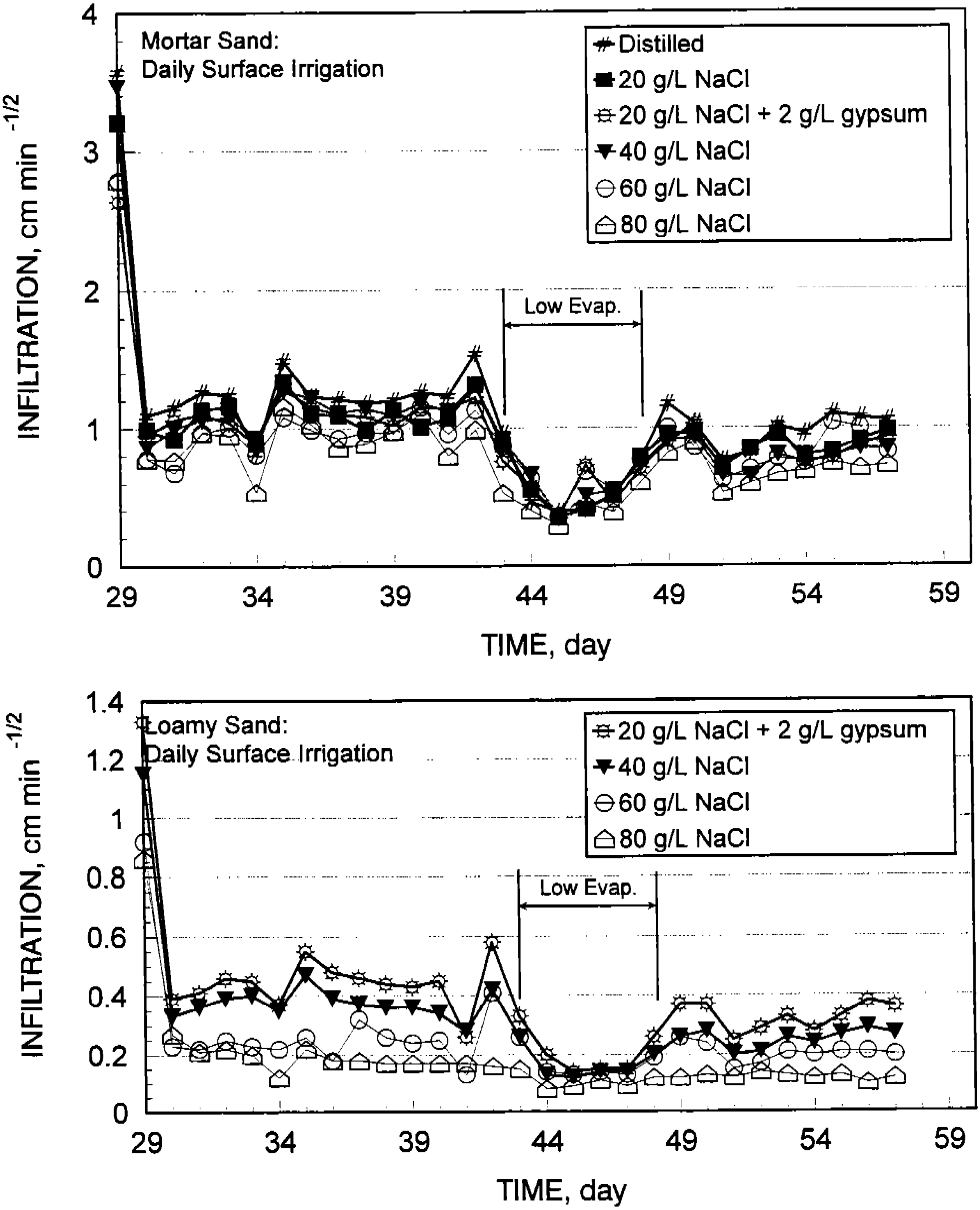

Figure 8-4. Changes in sorptivity into mortar sand and loamy sand under daily surface-irrigations at a leaching fraction of 0.10 following the drying process.

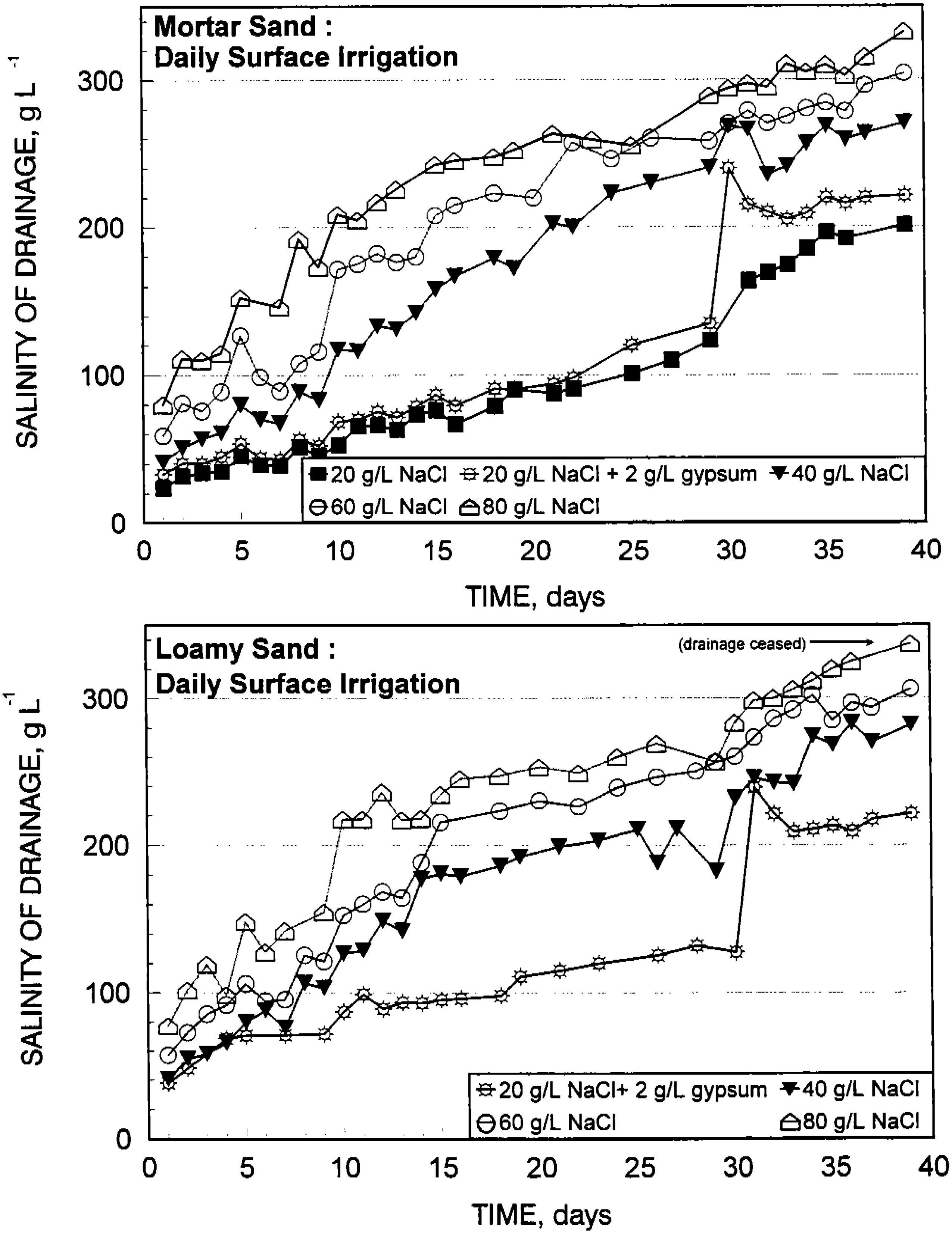

Figure 8-5. Salinity of drainage water from surface-irrigated mortar sand and loamy sand during the performance testing.

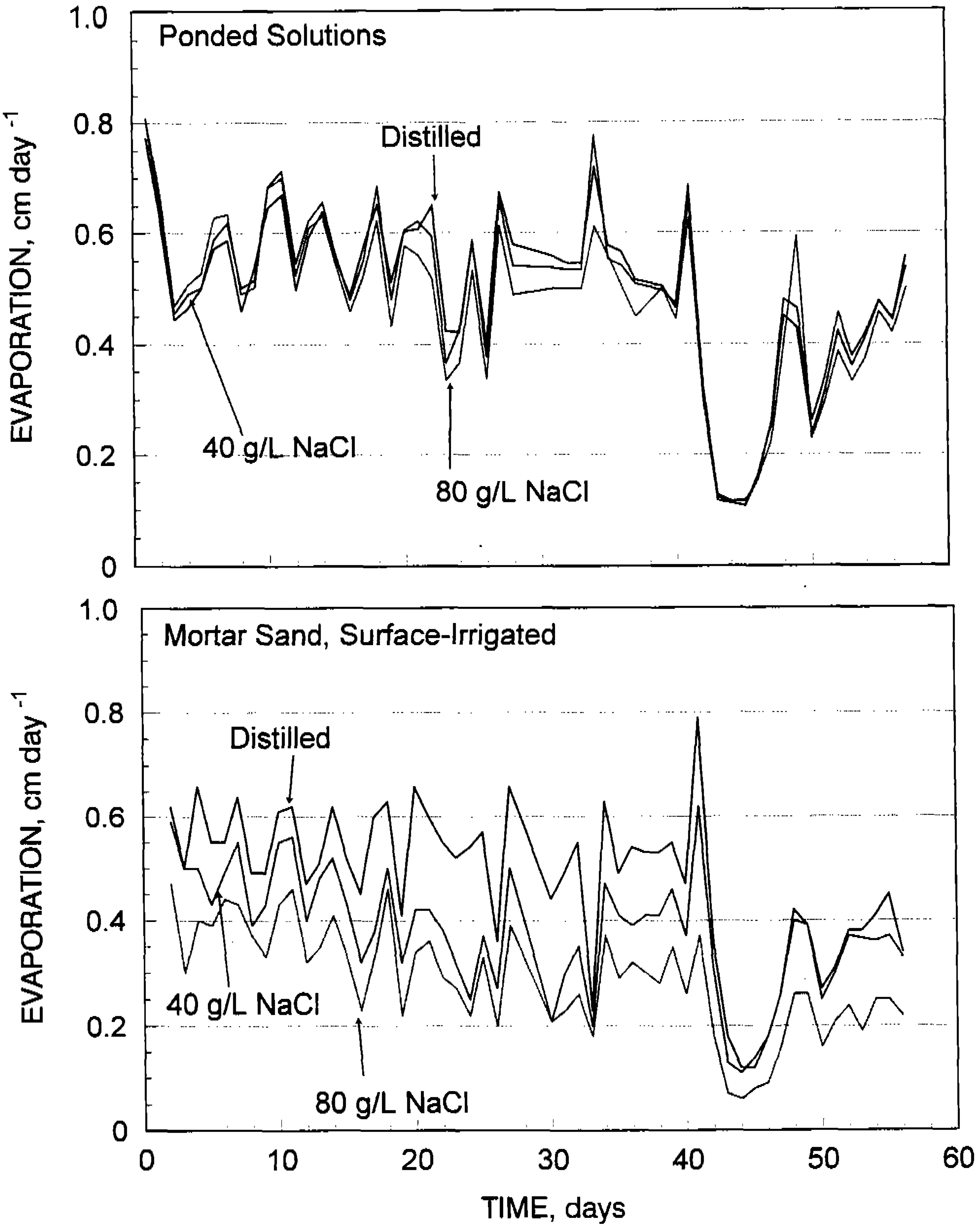

Figure 8-6. Daily water evaporation rates from ponded solutions and mortar sand (10.5) surface - irrigated daily.

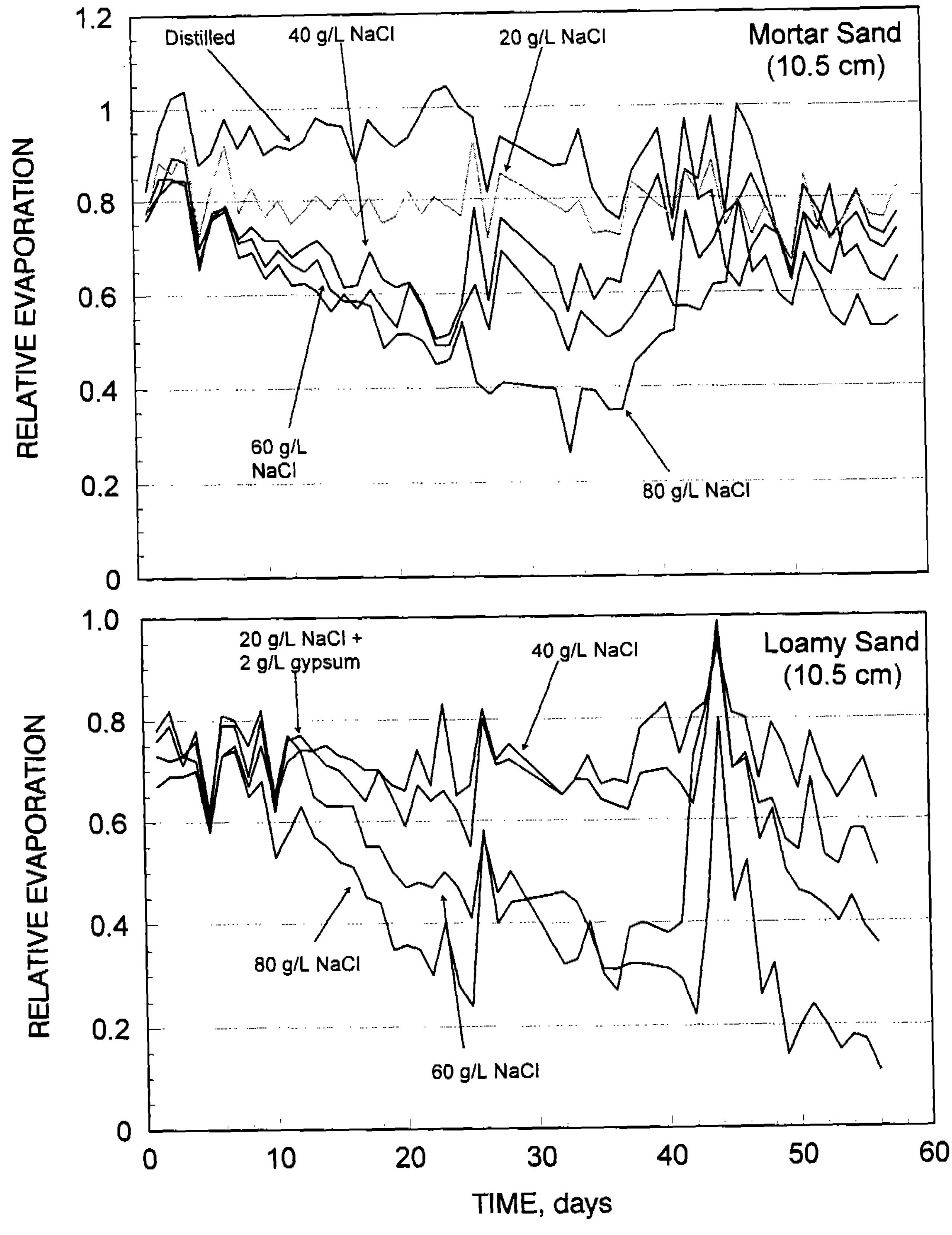

Figure 8-7. Relative water evaporation from surface-irrigated mortar sand and loamy sand during the performance testing.

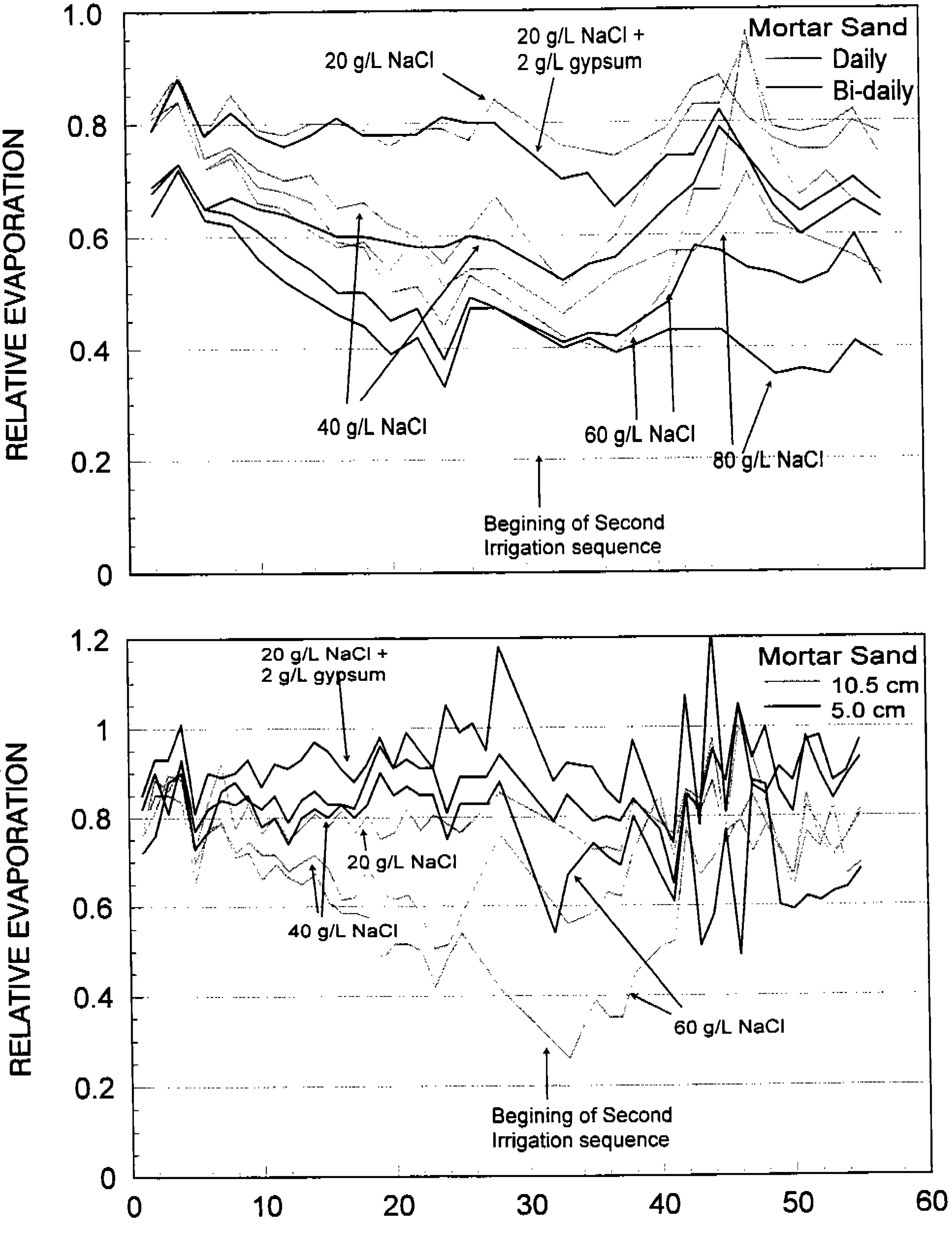

Figure 8-8. Relative water evaporation from sand-beds with surface-irrigated daily or bi-daily and different thickness during the performance testing.

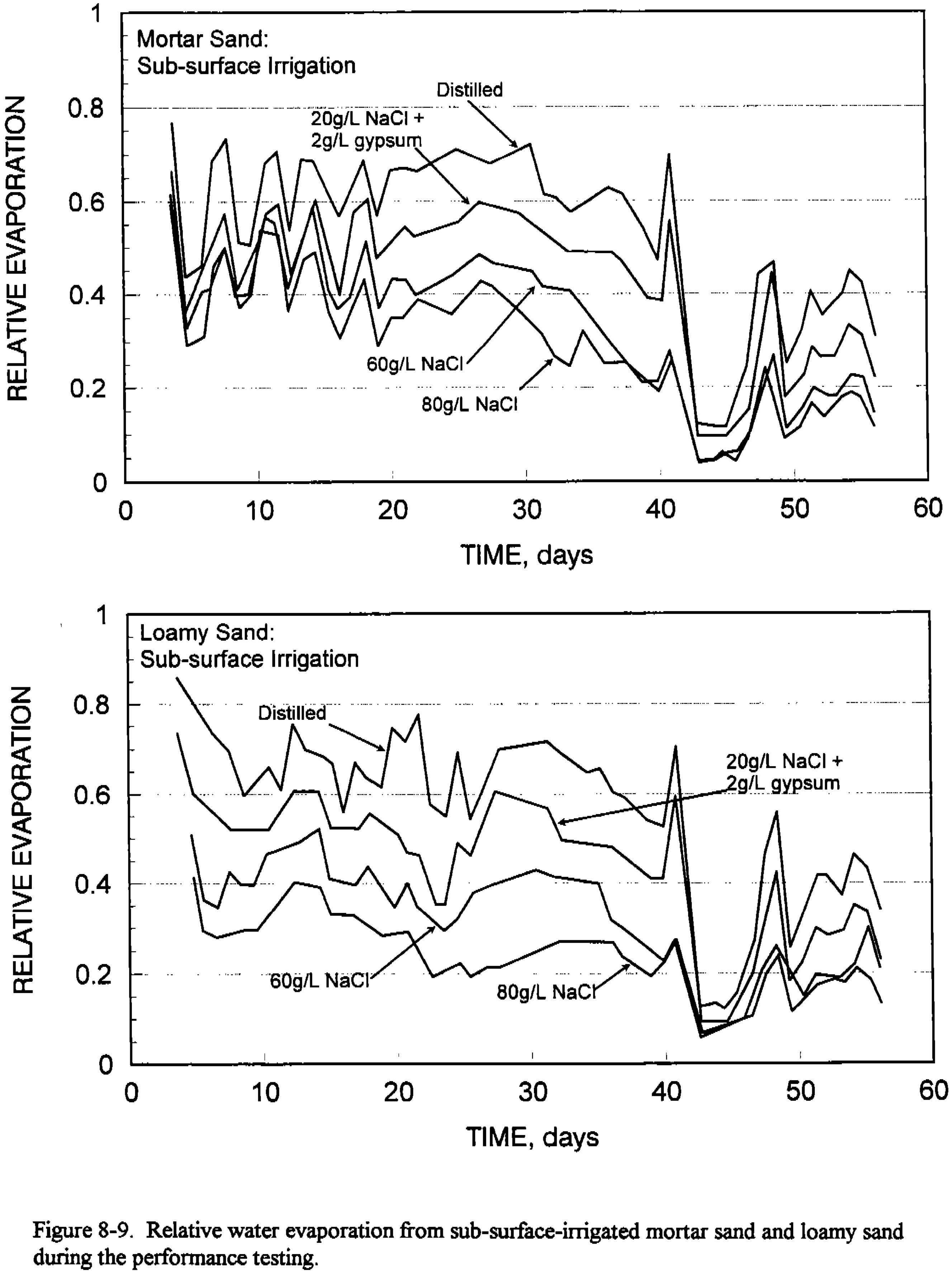

Figure 8-9. Relative water evaporation from sub-surface-irrigated mortar sand and loamy sand during the performance testing.