Spatial and Temporal Distribution of Salts on Fairways and Greens Irrigated with Reuse Water

D. A. Devitt,* M. Lockett, R. L. Morris, and B. M. Bird

ABSTRACT

A 4-yr study was conducted to assess the impact of reuse water on soil salinization of nine golf courses in southern Nevada: three long-term reuse courses, three fresh-water courses, and three courses that transitioned to reuse water during the experimental period. Four of nine fairways had positive leaching fractions (LFs) during all 4 yr, with statistical separation occurring based on 4-yr averages ($p < 0.001$). Soil salinity levels followed a sinusoidal seasonal curve, with 70% of all peaks associated with summer months. Salinity contour maps (surface soil) were compared over time. More than 85% of the surface area of greens were mapped as electrical conductivity of saturation extract (EC_e) < 4.0 dS m^{-1}, whereas 64% of the fairways were mapped at EC_e < 4.0 dS m^{-1}. This salinity relationship dropped to 13% on fairways of long-term reuse courses. Changes in the average EC_e values after transition to reuse water were primarily driven by the number of days a course had been irrigated with reuse water ($R^2 = 0.69$*). Depth-averaged salinity (sensors) was found to be highly correlated with LF on reuse courses ($R^2 = 0.86$***) and transitional courses ($R^2 = 0.87$***). Yearly changes in depth-averaged sensor values on transitional courses were described by an equation that included the number of days a golf course was irrigated with reuse water, the LF, and the uniformity of the irrigation system ($R^2 = 0.83$***). Although deficit irrigating can be practiced for short periods, adequate LFs are essential for the long-term success of golf courses irrigated with reuse water.**

THE Colorado River basin has been under an extended drought for the past 5 yr, raising long-term supply concerns with water managers. In the lower Colorado River basin (including California, Nevada, and Arizona), populations have continued to grow at a rapid pace, such as the fourfold increase in population in the Las Vegas valley over the past 20 yr. In response, water managers have sought new sources of water and more efficient ways to use it. Reuse water (i.e., treated sewage effluent) has been added to the water portfolios of many communities in the Southwest USA. The quantity of reuse water generated in most communities is fairly reliable. Even during times of drought, consumers typically do not significantly alter indoor water use (eg, showering, washing clothes, and flushing toilets). Thus, as the population increases, so does the amount of reuse water generated and discharged (Gary Grinnell, Southern Nevada Water Authority, personal communication, 2006) (Fig. 1). However, the extent to which communities use reuse water for irrigation purposes, the price they place on reuse water, and whether certain users such as golf courses are mandated to use reuse water varies from community to community (Devitt et al., 2004).

Las Vegas is somewhat unique in that it discharges reuse water back to Lake Mead and receives what is known as "return flow credits" on all water that can be documented to have a water signature from the Colorado River. As such, the majority of reuse water is returned to the Colorado River. However, in 1995, a "wastewater collection master plan" (Southern Nevada Water Authority, 1995) identified that a limitation in the wastewater collection system existed in areas of new growth located over 20 miles from the main facility. A feasibility study recommended the construction of satellite treatment plants for the treatment and distribution of reuse water for irrigation of nearby golf courses and parks. Three satellite treatment plants were constructed. Golf courses in close proximity to the distribution system were mandated to transition. Reuse water used for irrigation is priced and regulated the same as municipal water (equal value on a volume basis). The golf course industry has expressed concern over the impact such water may have on the long-term salt balances of golf courses, especially under water restrictions associated with periods of drought. In response to this mandated transition to reuse water and concerns about soil salinity, we conducted a 4-yr study to assess the impact of reuse water on golf courses in southern Nevada. We have previously reported on several aspects of this study (Devitt et al., 2004, 2005a, 2005b, 2005c). In this article, we present information on factors that influenced changes in surface soil salinity on a spatial and temporal basis on fairways and greens of nine golf courses irrigated with fresh water, reuse water, or fresh water transitioned to reuse water.

MATERIALS AND METHODS

A study was initiated in 2000 on nine golf courses (Table 1 and Table 2) located in the Las Vegas Valley: three long-term reuse courses (designated as B, L, and W), three freshwater courses (designated as P, R, and T), and three courses transitioning to reuse water during the monitoring period (designated as A, C, and S). Because the Colorado River basin was experiencing an extended drought, two of the fresh water courses (R and T) also transitioned during the latter part of this study. The new satellite treatment plants were not operating at full capacity during the transition period; thus, salt levels were lower than measured from the older treatment plants that provided reuse water to the long-term reuse courses (Table 1). Water meters, salinity sensors (Soil Moisture Corporation, Santa Barbara, CA), time domain reflectometry

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Abbreviations: CUC, Christiansen uniformity coefficient; EC_e, electrical conductivity of saturation extract; LF, leaching fraction.

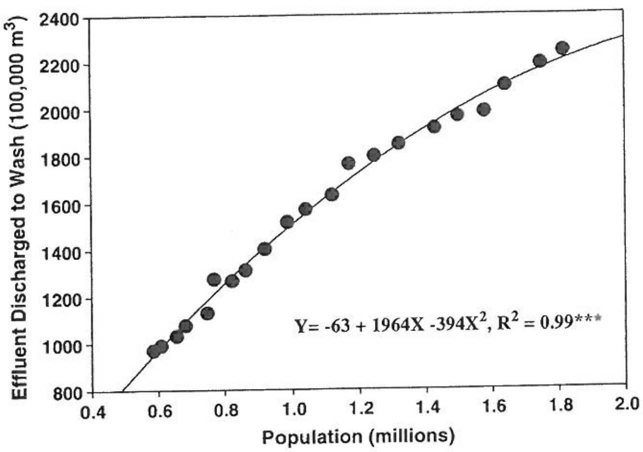

Fig. 1. Treated sewage effluent discharged (m^3) into the Las Vegas Wash (Clark County NV) as a function of population.

probes (Soil Moisture Corporation, Santa Barbara CA), and solution extraction cups were installed on a fairway and green of each golf course. All sensors and solution cups were installed in a nested array, positioned at depths of 15, 45, 75, and 105 cm. Measurements were recorded twice per month. Depth-averaged salinity was estimated by averaging sensor values from all four depths. All courses were monitored for 1600 d. In spring of 2001, 2002, 2003, and 2004, soil samples were taken from the monitored fairway and green of each course. Samples were taken to a depth of 15 cm in a 5 by 5 grid (offset 15 cm each year). Grid locations were spaced 2.74 m apart. Soil samples were bagged and transported in coolers back to the lab where subsamples were weighed, oven dried, and weighed a second time to estimate gravimetric water contents. The remaining soil was used for saturation extracts, following the procedures of

Table 1. Site characteristics.

Golf course	Irrigation status	EC water	Turfgrass (fairway/green)‡
		dSm^{-1}	
P	fresh	0.80	Common bermudagrass/'SR1020' creeping bentgrass
B	reuse	2.00	Common bermudagrass/'Penlinks' creeping bentgrass
L	reuse	2.07	'Tifway' hybrid bermudagrass/ 'Tifgreen' hybrid bermudagrass
W	reuse	2.22	'Tifway' hybrid bermudagrass base and common bermudagrass/ 'TifEagle' hybrid bermudagrass
A	transition	0.98/1.51†	Common bermudagrass base plus annual bluegrass/'Tifgreen' hybrid bermudagrass base plus annual bluegrass (2001), 'Tifdwarf' hybrid bermudagrass (2002–2004)
C	transition	0.95/1.40	'Tifway' hybrid bermudagrass/ 'Pencross' creeping bentgrass
R	transition	0.99/1.40	Blend of 50% 'Palmer' perennial ryegrass, 50% 'Prelude' perennial ryegrass (2001); 'NuMex Sahara' common bermudagrass (2002–2004)/SR1020 creeping bentgrass
S	transition	0.95/1.46	'Tifway' hybrid bermudagrass/33% Providence creeping bentgrass 33% SR 1020 creeping bentgrass 34% SR 1119 creeping bentgrass
T	transition	0.89/1.42	'Tifway' hybrid bermudagrass/ 'Penlinks' creeping bentgrass

† EC of fresh water/EC of reuse water.
‡ Common bermudagrass (*Cynodon dactylon* (L.) *Pers.*); Hybrid bermudagrass (*Cynodon dactylon* (L.) Pers. × *Cynodon transvaalensis* Burtt-Davy); Creeping bentgrass (*Agrostis palustris* Huds.); Perennial ryegrass (*Lolium perenne* L.); Annual bluegrass (*Poa annua* L.).

Table 2. Soil classification for fairways and greens.†

Course	Description
A	Cave gravelly fine sandy loam (loamy, mixed, thermic, shallow Typic Paleorthids)
B	Arizo very gravelly fine sandy loam (sandy-skeletal, mixed, thermic Typic Torriorthents)
C	Cave gravelly fine sandy loam (loamy, mixed, thermic, shallow Typic Paleorthids)
L	Arizo extremely stony loam (sandy-skeletal, mixed, thermic Typic Torriorthents)
P	Glen carb very fine sandy loam (fine-silty, carbonatic, thermic Typic Torrifluvents)
R	Cave gravelly fine sandy loam (loamy, mixed, thermic, shallow Typic Paleorthids)
S	Cave gravelly fine sandy loam (loamy, mixed, thermic, shallow Typic Paleorthids)
T	Cave gravelly fine sandy loam (loamy, mixed, thermic, shallow Typic Paleorthids)
W	McCarran fine sandy loam (coarse-loamy, mixed, thermic Cambic Gypsiorthids)

† All greens were designed and constructed meeting USGA standards.

the U.S. Salinity laboratory (U.S. Salinity Laboratory Staff, 1954). Extracts were analyzed for electrical conductivity using a Beckman conductivity bridge and reported in units of $dS\ m^{-1}$. Surface soil volumetric water contents (0–5 cm depth) were estimated with a theta probe (Dyanmax, Houston, TX) at all grid locations before soil sampling.

Leaching fractions (LF) were estimated for all fairways by defining LF as (irrigation − evapotranspiration [potential evapotranspiration × crop coefficients])/irrigation. Irrigation was estimated from volume (water meter) precipitation curves established for each site. Evapotranspiration was estimated by using locally derived crop coefficients (Devitt et al., 1992) and potential evapotranspiration estimates (Penman-Monteith Equation [Monteith and Unsworth, 1990]) from local automated weather stations. Irrigation system uniformities (Christiansen uniformity coefficients [CUCs]) Hart and Reynolds, 1965) were evaluated for each fairway and green before initiation of the study, using a 5 by 5 grid of cups (2.74 m spacing) in the irrigation zone containing the sensor location.

Data were analyzed using descriptive analysis, ANOVA, and/or linear and multiple regression analysis. Multiple regressions were performed in a backward stepwise manner, with deletion of terms occurring when p values for the t test exceeded 0.05. To eliminate the possibility of co-correlation, parameters were included only if variance inflation factors were less than 3 and the sum total was less than 10 (Systat Software, 2004). If the accepted variance inflation factor was exceeded, parameters were eliminated, and regressions were run a second time. Gravimetric water content and electrical conductivity data from each grid location were kriged using Geostatistics for Environmental Sciences, version 7.0 (Gamma Design Software, Plainwell, MI). The area within each kriged contour interval was estimated by the ratio of the isolated unit color area in pixels to the total area in pixels. Unit color pixels were separated and counted by using an image processing technique that takes the histogram of an image and counts the number of pixels in the image that fall within each color category (Image Pro Version 3.0; Media Cybernetics, Silver Spring, MD).

RESULTS

Irrigation

Total irrigation amounts (I), estimated evapotranspiration, leaching fractions (LF), and irrigation system uniformities (CUCs) are reported in Table 3 for all nine fairways. On greens, because of looped irrigation sys-

Table 3. Irrigation, estimated evapotranspiration (ET), leaching fraction (LF), and Christiansen uniformity coefficient (CUC; year 1 only, including greens) for all nine fairways measured in years 1–4.

		Golf course								
	Year	A_T†	B_R	C_T	L_R	P_F	R_T	S_T	T_T	W_R
Irrigation, cm	1	132.0	156.4	166.5	182.8	121.0	222.5	136.0	113.7	111.4
	2	123.8	201.1	221.0	238.1	141.2	278.4	174.0	145.8	134.2
	3	119.2	189.6	169.8	213.0	138.8	304.4	135.0	191.2	120.0
	4	95.8	153.0	138.3	204.2	108.8	232.5	108.8	142.4	153.3
ET, cm	1	125.0	125.1	125.0	125.8	125.8	140.4	125.8	125.8	126.0
	2	156.3	160.5	162.5	156.8	158.8	179.0	158.8	159.7	158.4
	3	151.2	150.3	151.9	151.6	151.3	168.7	150.4	150.0	151.4
	4	127.1	128.0	127.2	127.0	127.3	139.5	127.3	127.2	123.1
LF	1	+0.05	+0.20	+0.25	+0.31	−0.04	+0.37	+0.08	−0.11	−0.13
	2	−0.26	+0.20	+0.26	+0.34	−0.12	+0.36	+0.09	−0.10	−0.18
	3	−0.27	+0.21	+0.11	+0.29	−0.09	+0.45	−0.11	+0.21	−0.26
	4	−0.33	+0.16	+0.08	+0.38	−0.17	+0.40	−0.12	+0.11	+0.20
CUC	Fairways	0.77	0.92	0.84	0.77	0.78	0.87	0.89	0.87	0.83
	Greens	0.85	0.86	0.84	0.79	0.78	0.82	0.91	0.86	0.90

† Irrigation treatment. T = transition; R = reuse; F = fresh.

tems and the fact that we were required to place monitoring locations on the fringe of the greens, we were unable to accurately estimate irrigation depths at the sensor locations. The water balance approach used in this study assumes that crop coefficients published for the area are appropriate (Devitt et al., 1995) and that the coefficients were the same for turf irrigated with fresh water (0.80–0.98 dS m^{-1}) or reuse water (1.45–2.1 dS m^{-1}).

The negative LFs reported in Table 3 are theoretical and occur based on the estimates of estimated evapotranspiration being greater than the irrigation amounts. Although a negative LF means that no leaching is taking place (as would an LF of 0), the magnitude of the negative LF reflects the degree to which deficit conditions are occurring. In previous work with tall fescue under controlled and quantifiable deficit irrigations (LF as low as −0.40) (Brown et al., 2004), no statistical difference in evapotranspiration estimated via lysimeters occurred between tall fescue irrigated with a LF of +0.15 and −0.25 during a summer in Las Vegas, NV.

The average leaching fractions on the fairways showed a nonsignificant trend over time (average LFs for years 1, 2, 3, and 4 of 0.11, 0.07, 0.06, and 0.08, respectively). However, individual courses showed significant changes in LF over the 4-yr period, as noted for courses T, S, and W, that changed from positive to negative LFs or from negative to positive LFs. Only four of the nine fairways had positive LFs in all 4 yr, with statistical separation between courses based on the 4-yr averages ($p < 0.001$). Two of the courses had excessive LFs (>0.30), two courses had LFs close to the locally recommended value of 0.15, one course had an inadequate positive LF (0.03), and four courses had average LFs that were negative for the 4-yr period.

Irrigation system uniformity coefficients measured at the beginning of the experiment (Table 3) ranged from 0.78 to 0.91 on greens and from 0.77 to 0.92 on fairways, with no statistical difference between mean CUC values on fairways and greens (0.85 vs. 0.84; $p > 0.05$). There was a weak curvilinear relationship ($p < 0.10$) between CUCs for fairways and greens. Although we did not measure irrigation uniformities throughout the study, we did assess the uniformity of soil volumetric water contents (theta probe) estimated at the 5 by 5 grid locations. The average CUCs for surface soil water content on the fairways of the nine golf courses (0.81–0.93) had a similar range as the irrigation system uniformities (0.77–0.92, no significant correlation between the two CUCs), suggesting that if the irrigation distribution and infiltration patterns changed with time, the changes were minimal (i.e., no visual pattern in turfgrass response was observed). Moisture redistribution in the soil could mask variability in the actual irrigation water distribution pattern (90% of site years had CUCs of $\theta \geq 0.84$ on fairways). The CUCs for surface soil water content on the greens of the nine golf courses were higher (0.84–0.97) but not statistically different from the fairways ($p > 0.05$).

Soil Salinity

Soil salinity was measured with in situ sensors on fairways and greens. Soil salinity measured at the 15-cm depth is plotted over the 1600-d monitoring period for each golf course in Fig. 2. Surface soil salinity measured at these single point locations was highly variable over time (4.8–21.0 dS m^{-1} on greens and 4.9–40 dS m^{-1} on fairways). The temporal response of soil salinity at the surface at most courses followed a sinusoidal shape, with distinct peaks during summer time periods. In fact, 70% of all salinity peaks were associated with summer time periods (examine peaks in association with July labels shown in Fig. 2). There was a 36% greater number of salinity peaks associated with fairways than greens, suggesting that more favorable water balances were being maintained on greens. Soil salinity was greater at the 15-cm depth in fairways than greens in five of the courses ($p < 0.001$) (all long-term reuse courses plus the longest transition course A); however, in two of the courses, soil salinity was higher in the greens than in the fairways (transition courses C and S; $p < 0.001$), and in

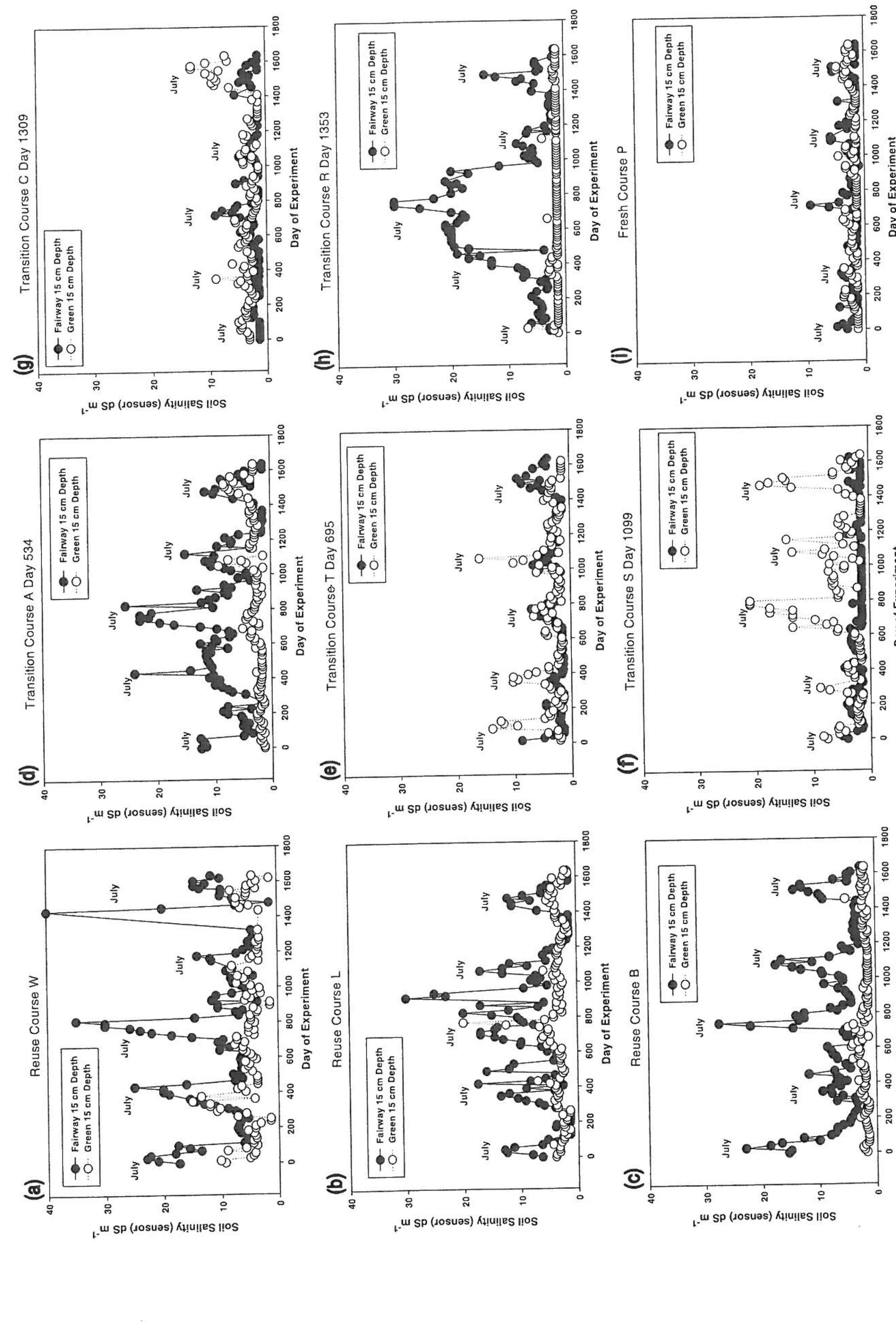

Fig. 2. Soil salinity at the 15-cm depth (sensors) monitored over 1600 d on fairways and greens irrigated with reuse water, fresh water, or fresh water transitioned to reuse water. The day number listed for transition courses indicates the day of experiment the course switched to reuse water.

two courses there was no statistical difference (fresh course P and transition course T). Although fresh water golf course P exhibited few distinct summertime peaks with none exceeding 10 dS m^{-1}, all transition courses (still freshwater irrigated) revealed multiple distinct peaks before transition, with three of the five transition courses exceeding 20 dS m^{-1} in the soil solution (two fairways and one green). Such peaks before transition would imply that deficit irrigation during summer time periods can lead to significant concentration of salts in surface soils even when irrigating with Colorado River water (~0.95 dS m^{-1}). The fact that near-surface salinity returned to low values (<5.0 dS m^{-1}) during winter months indicates that the near-surface soil region is dynamic and transient. Transition golf course R had soil salinity values as high as 30 dS m^{-1} before transition. Although leaching fractions on a yearly basis should have been adequate to control salinity, the golf course opened just before the initiation of the study, and we speculate that native salts (crushed caliche, highly calcareous soil) played a significant part in the pretransition peaks observed on the fairway (both magnitude and width).

Over the course of the 4-yr study, 1800 soil samples were taken on the fairways and greens of the nine golf courses (0–15 cm). Soil salinity and gravimetric water content (average plus SD) are reported in Tables 4 and 5. ANOVAs indicated significant course, year, and course by year interactions for soil salinity and gravimetric water contents (fairways and greens; $p <$ 0.001). Soil salinity was highest on reuse irrigated fairways, with average values exceeding 15.0 dS m^{-1} during the third year on golf course W. Salinity values were lower on greens, even when irrigated with reuse water, with the one exception of golf course S, which had poor internal drainage and was rebuilt at the end of the experiment. The average CV associated with the electrical conductivity of saturation extract (EC$_e$) measured in fairway grid samples from long-term reuse courses (0.39) was higher and statistically different ($p < 0.001$) from transition and fresh water courses (0.29). There was no significant difference in the CV of EC$_e$ measured in grid samples from greens or with gravimetric water contents from fairways or greens. Ninety-two percent of the golf course years (nine courses, 4 yr) had greater than 85% of the surface area mapped as EC$_e$ < 4.0 dS m^{-1} on greens, whereas only 64% of golf course years on fairways had greater than 85% of the surface area mapped as EC$_e$ < 4.0 dS m^{-1}, dropping to 13% on long-term reuse courses. As courses transitioned to reuse water, the spatial patterns of soil salinity on fairways changed (Fig. 3, transition course A). The percent surface area with EC$_e$ > 4.0 dS m^{-1} increased each year after golf course A transitioned to reuse water (year 1: 3.4%; year 2: 23.1%; year 3: 42.8%; and year 4: 100%), with area increasing as LFs declined. Spatial patterns of surface soil salinity on long-term reuse fairways also revealed changes with time, apparently driven by changing leaching fractions. For example, as the LF increased from −0.26 to +0.20 on reuse course W (2003 vs. 2004), the percent area with EC$_e$ values greater 8.0 dS m^{-1} dropped from 100% to 26.4% (Fig. 4).

The EC of the irrigation water accounted for 43% of the variability ($p < 0.001$) in the average EC$_e$ values (0–15 cm) for all courses and years and accounted for 51% of the variability in the percent area on fairways mapped with EC$_e$ > 4.0 dS m^{-1}. This increased to 74% if the correlation was based on maximum grid EC$_e$ values on transition courses (not including course R because of high native salts). The change in the average EC$_e$ values after transitioning to reuse water (course R not included) from year to year was shown to be primarily a response to the number of days a course had been irrigated with reuse water ($\Delta EC_e = 0.302 + 0.0018$ [days irrigated with reuse water]; $R^2 = 0.69$***). Based on the results of this study, the equation predicts that it would take 1000 d to increase the average surface EC$_e$ values by 2.1 dS m^{-1}.

Soil salinity measured in the 0- to 15-cm soil extracts was significantly correlated with soil salinity measured with sensors at the 15-cm depth ($R^2 = 0.52$*** fairways; $R^2 = 0.46$*** greens). An improved correlation with fairway soil salinity in the 0- to 15-cm extracts occurred with depth-averaged sensor values (0–120 cm) ($R^2 =$ 0.77*** fairways; $R^2 = 0.36$ greens) (Fig. 5), reflecting the greater variability in sensor values near the surface. Salinity sensor values (15 cm depth) obtained at the same time soil samples were taken were poorly cor-

Table 4. Electrical conductivity of saturation extract (EC$_e$) and gravimetric water contents (0–15 cm) for all nine fairways measured in years 1–4.

Year	Golf course								
	A_T†	B_R	C_T	L_R	P_F	R_T	S_T	T_T	W_R
					EC$_e$, dS m^{-1}				
1	2.83a‡	3.08a	3.22a	6.40a	2.22a	4.39a	2.60a	2.03a	11.48b
2	3.92a	4.66ab	3.84a	9.37b	3.17a	9.50c	2.48a	3.74b	11.64b
3	4.18ab	5.92bc	4.20a	9.19b	2.84a	6.41b	2.80a	3.32ab	15.21c
4	5.54b	4.24a	4.20a	7.17a	2.84a	7.36b	3.58a	3.47ab	7.89a
					Gravimetric water content, kg kg^{-1}				
1	0.091bc	0.114a	0.116ab	0.083a	0.183a	0.110a	0.127ab	0.072ab	0.182b
2	0.110c	0.128ab	0.123ab	0.111b	0.177a	0.104a	0.138b	0.062a	0.271c
3	0.097bc	0.092a	0.127b	0.110b	0.223b	0.103a	0.108a	0.103c	0.153a
4	0.066a	0.126ab	0.097a	0.117b	0.180a	0.128a	0.105a	0.089bc	0.189b

† Irrigation treatment. T = transition; R = reuse; F = fresh.
‡ Means in same column followed by a different letter are significantly different by Duncan's multiple range test ($p < 0.05$).

Table 5. Electrical conductivity of saturation extract (EC_e) and gravimetric water contents (0–15 cm) for all nine greens measured in years 1–4.

Year	A_T†	B_R	C_T	L_R	P_F	R_T	S_T	T_T	W_R
					EC_e, dS m^{-1}				
1	2.13c‡	1.61b	2.13a	2.85b	1.62a	0.82a	3.51b	2.41b	1.93b
2	3.32d	1.40b	2.17a	2.77b	1.59a	0.92a	4.17c	2.06ab	2.10bc
3	1.60b	0.85a	2.02a	3.10b	1.26a	1.03a	3.15a	1.71a	2.42cd
4	1.27a	2.38c	3.16b	2.49a	3.85b	1.03a	4.61d	2.64bc	1.40a
					Gravimetric water content, kg kg^{-1}				
1	0.191b	0.167a	0.088a	0.128a	0.209b	0.119a	0.112ab	0.069a	0.097a
2	0.176b	0.194b	0.122b	0.137a	0.163a	0.125a	0.130b	0.076a	0.132b
3	0.068a	0.175a	0.124b	0.161b	0.202b	0.125a	0.095a	0.082a	0.126b
4	0.073a	0.158a	0.114b	0.119a	0.332c	0.125a	0.099a	0.072a	0.096a

(Golf course spans columns A_T through W_R.)

† Irrigation treatment. T = transition; R = reuse; F = fresh.
‡ Means in same column followed by a different letter are significantly different by Duncan's multiple range test ($p < 0.05$).

related with leaching fractions ($p > 0.05$). By contrast, LF was correlated with EC_e, accounting for 51% of the variability in the average surface soil EC_e values on transition courses and 48% on reuse courses. Depth-averaged soil salinity (sensors) had even higher correlations, with LF (Fig. 6) in both reuse courses ($R^2 = 0.86$***) and transitional courses ($R^2 = 0.87$***). Salinity sensor values increased as the EC_i increased and

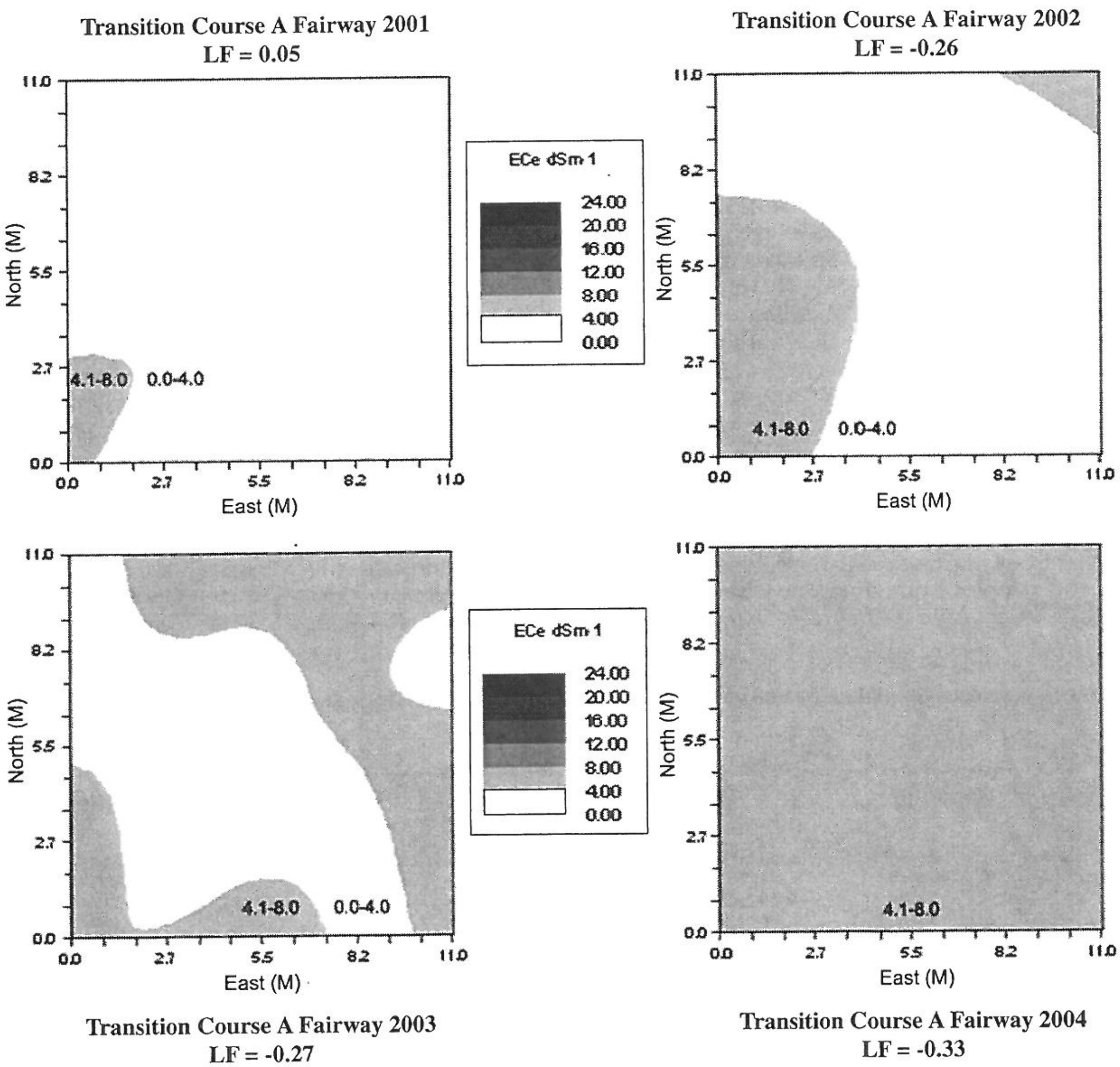

Fig. 3. Spatial distribution (m) of surface soil salinity (electrical conductivity of saturation extract [EC_e], 0–15 cm) on transition course A for years 1 through 4.

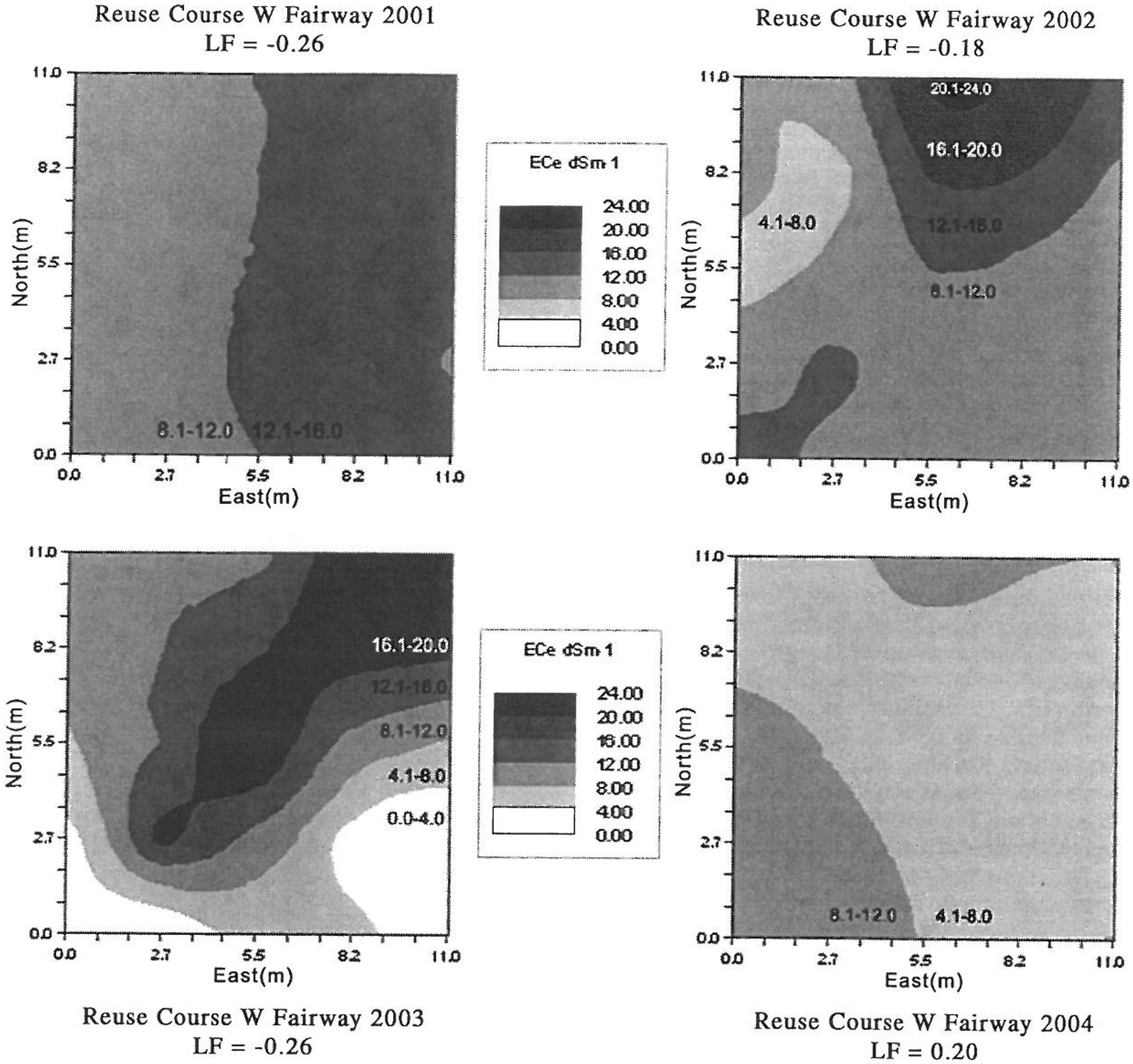

Fig. 4. Spatial distribution (m) of surface soil salinity (electrical conductivity of saturation extract [EC_e], 0–15 cm) on long-term reuse course W for years 1–4. LF, leaching fraction.

the CUC decreased (sensor salinity 15 cm = 13.3 + 5.1[EC_i] − 17.9[CUC]; R^2 = 0.54***). Yearly change in depth-averaged sensor values on transitional courses (course R not included) could be described by an equation that included the number of days a golf course was irrigated with reuse water, the LF, and the CUC of the irrigation system (ΔEC sensor = 11.43 + 0.0031[Days] − 12.57[CUC] − 4.29LF; R^2 = 0.83***). When all data were combined, multiple regression analysis indicated that fairway depth-averaged soil salinity (sensors) could be described by an equation that included the LF and EC of the irrigation water (EC_i) (R^2 = 0.67***) (Fig. 7). On greens, only EC_i was correlated with the depth-averaged soil salinity (R^2 = 0.53***).

DISCUSSION

The quality of reuse water in the USA varies by region, level of treatment, and quality of the source water (Devitt et al., 2005b; U.S. Golf Association, 1994). For communities in the lower Colorado River basin, the Colorado River carries over 900 kg of salt per megaliter of water (1 ton of salt per acre foot of water). By the time this water is used, treated, and discharged as reuse water, there is a near doubling in the salt load (Devitt et al., 2005b). The level of salt does not preclude its use as a viable alternative irrigation source (Lazarova and Bahri, 2005; U.S. Golf Association, 1994). Rather, it means that proper irrigation management practices must be implemented and that superintendents (and other landscape managers) must be alert to changes in the status of their turfgrass system when using such water (Dean et al., 1996; Leskys et al., 1999; Hayes et al., 1990; Mancino and Pepper, 1992).

Soil salinity, as measured with sensors at the 15-cm depth, demonstrated how values changed with time, with many courses exhibiting extremely high levels peaking during summer time periods. These peaks reflected the deficit irrigation practices that occur on many fairways during summer months. These peaks signifi-

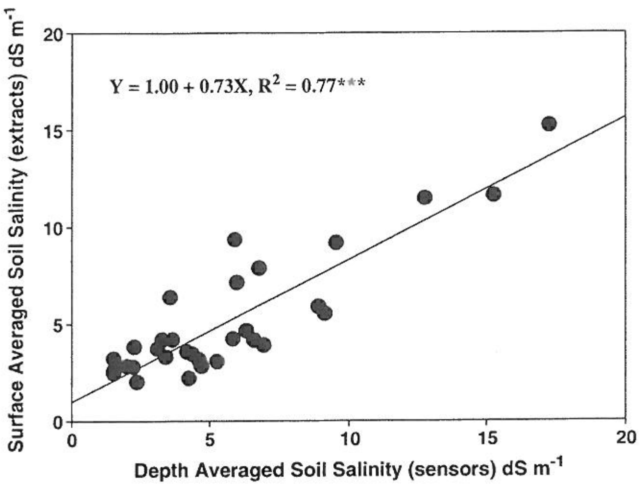

Fig. 5. Fairway surface averaged soil salinity (electrical conductivity of saturation extract, 0–15 cm) as a function of depth averaged soil salinity (sensors) for all 4 yr.

cantly declined during winter periods when more favorable water balances could be maintained. The EC_e was found to be highly correlated with the depth-averaged sensor values ($R^2 = 0.77$***). If adjusted for soil moisture content, surface soil salinity was approximately 40% higher than depth-averaged values, reflecting the impact of inadequate leaching. Although sensors provide a convenient way to assess soil salinity, values from sensors represent a single point in place and time, and the cost of sensors makes it prohibitive for area-intensive sampling. Soil sampling represents an integrated estimate over a given depth interval that could be further integrated over space by intensive grid sampling (still a labor and cost factor).

Depth-averaged sensor values (and we assume depth-averaged EC_e values) provided a clear picture of salinization and were found to be highly correlated with the LF, indicating that the depth-averaged profile values could be used to assess the relative magnitude of the LF,

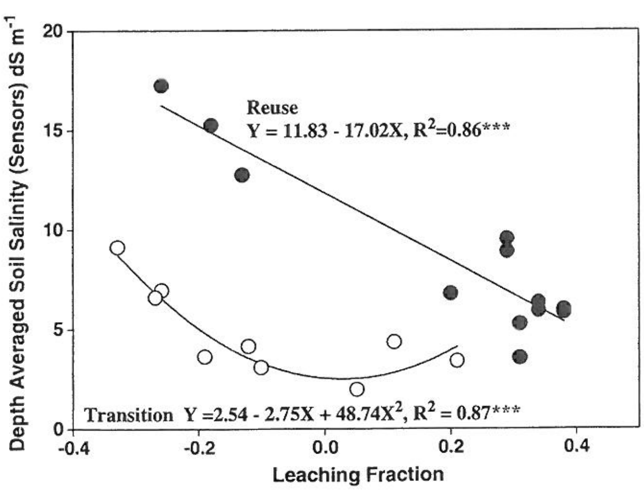

Fig. 6. Fairway depth-averaged soil salinity (sensors) as a function of leaching fraction for all reuse courses vs. transition courses (yearly data).

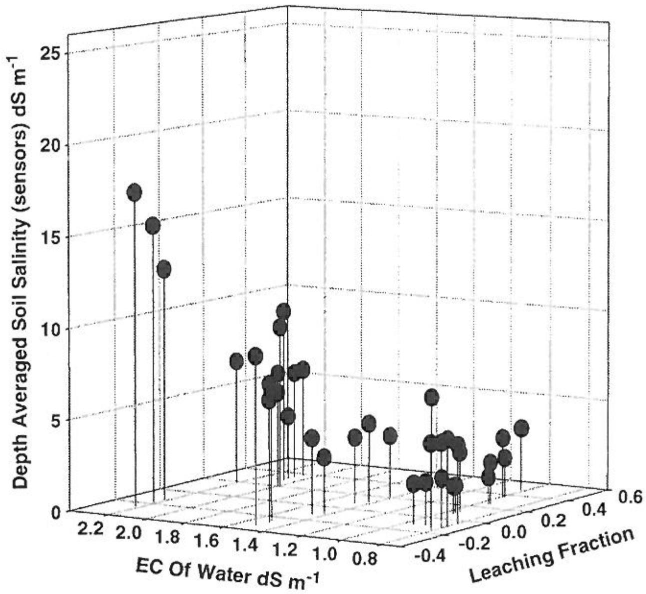

Fig. 7. Fairway depth-averaged soil salinity (sensors) as a function of the electrical conductivity (EC) of the irrigation water and the leaching fraction ($EC_e = -1.72 + 5.23ECi - 6.52LF$; $N = 36$; $R^2 = 0.67$***).

which can be defined as a concentration factor that operates on the scale of the root zone. Only four of the nine courses maintained positive LFs on the fairways over all 4 yr. Negative LFs had a significant effect on surface patterns and depth-averaged soil salinity. As the LF decreased when using waters of higher salt content, the impact of lower irrigation uniformities magnified the spatial patterns of salinity, as was shown for golf course A. LFs were calculated based on the assumption that locally derived crop coefficients were appropriate even under increasing levels of salinity. We have unpublished data to suggest that, at least up to depth-weighted EC_e values of approximately 12 to 15 dS m^{-1} (~27 dS m^{-1} soil solution), this is the case for bermudagrass [*Cynodom dactylon* (L.) Pers.]. Future research should define the range in soil salinity that crop coefficients are appropriate for various turfgrass species.

We could account for 83% of the variability in the yearly change in depth-averaged sensor values by knowing the number of reuse irrigation days, the LF, and the CUC, with change increasing as days increased and LF and CUC decreased. For example, after a 1000-d transition period, contrasting CUC and LF combinations of 0.75 (CUC) and 0.00 (LF) with 0.90 (CUC) and 0.15 (LF) led to a near doubling in the predicted ΔECe values (5.10 dS m^{-1} vs. 2.58 dS m^{-1}). Depth-averaged soil salinity was predicted to increase by as much as 41% when courses receiving 100% fresh water with a LF of +0.15 were contrasted with courses receiving 100% reuse water with a 0.00 LF (5.15 dS m^{-1} vs. 8.74 dS m^{-1}). Salinity at the 15-cm depth (sensors) was predicted to increase 52% for a course receiving reuse water with a CUC of 0.75, compared with a course receiving fresh water with a CUC of 0.90. These relationships between soil salinity and the salinity of the irrigation water, the LF imposed, and the CUC indicate that management can have a large impact on soil salinization. As the salinity of the reuse water increases, turfgrass managers will need to optimize the uniformity of the irrigation systems and apply additional water to achieve adequate leaching. Increasing the uniformity and maintaining these higher levels will lead to higher maintenance costs, and increasing the LF will lead to higher water costs. Management must be informed of these associated cost increases before transitioning to reuse water.

Irrigating with reuse water (~2.0 dS m^{-1}) requires an LF sufficient to control salinity. Those courses transitioning to reuse water never received full reuse water because the satellite plants were not operating at full capacity (EC_i ~1.5 dS m^{-1}). Fig. 3 and 6 suggest that combining reuse water (higher EC_i values) with low LFs results in a rapid rise in surface soil salinity, such as noted for golf course W (values as high as 40 dS m^{-1} and depth-averaged salinity values as high as 17 dS m^{-1} [sensors]). Although courses that transitioned to reuse water had lower salinity levels than found on long-term reuse courses, results suggest that it would only take a few years of continued deficit irrigation to reach threshold salinity values for grasses on fairways and greens (Marcum, 2000; Marcum and Pessarakli, 2000). Significant changes in LF (negative to positive as noted for reuse course W, comparing years 3 and 4) can have a rapid impact on surface salinity (typically the zone of highest root density), indicating the value of manipulating the LF based on soil monitoring feedback (Leskys et al., 1999). However, because of limited water resources, increasing populations, and an extended drought in the lower Colorado River basin, some communities in the basin are choosing to regulate reuse water in the same manner as fresh water. This means that when the highest drought management stages are implemented, many reuse courses will face the difficult choice of deficit irrigating with lower-quality reuse water or reducing turfgrass area (Brown et al., 2004; Fry and Butler 1989). Although deficit irrigation can be practiced for short periods, adequate LFs are essential for the long-term success of reuse irrigated golf courses.

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