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INTERNAL DRAINAGE THROUGH FINE-TEXTURED SUBSOILS AT TWO SITES IN NORTH DAKOTA

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ABSTRACT. *To determine if the internal drainage (downward movement of water out of the root zone) was adequate, we measured the movement of water out of the root zone in bordered plots planted to alfalfa. We applied three water quantity treatments: irrigation plus precipitation equal to one, two, and three times the calculated evapotranspiration (1ET, 2ET, and 3ET); and two irrigation water quality treatments: electrical conductivity (EC_{iw}) of 0.1 S/m, and sodium adsorption ratio (SAR_{iw}) of 4 and EC_{iw} = 0.34 S/m, SAR_{iw} = 16. Each treatment was replicated three times. Internal drainage amounts during the irrigation season (1 July to about 1 October) were as great as 843 mm. For the seven years at one site, the internal drainage averaged 585 mm, or 66% of the water applied (irrigation plus precipitation) to the 3ET treatment. Increased water application resulted in increased internal drainage. Irrigation with the 0.34 S/m water resulted in greater internal drainage (compared to irrigation with the 0.1 S/m water) at one site, but not at the other site. The 3ET treatment maintained soil water content near field capacity for the entire irrigation season, but a persistent perched water table was not detected. Internal drainage from the 3ET treatments exceeded the total water applied (irrigation plus precipitation) to the 1ET plots for 9 of the 12 site years. The tested soils have sufficient internal drainage capacity to allow supplemental irrigation without forming a perched water table.* ***Keywords.*** *Irrigation, Alfalfa (*Medicago sativa *L.), Glacial till soils.*

Lack of timely and adequate water is the limiting factor to crop production in the semiarid Northern Great Plains. The highly variable precipitation during the growing season exerts a strong influence on crop yields and limits crop choices. Supplemental irrigation is a management option that can improve crop yields, stabilize crop production, and expand crop rotation choices. Irrigation is an economically viable option for producers, increasing net returns by $86 to $267/ha for three areas of North Dakota (Leitch et al., 1991).

Alfalfa (*Medicago sativa* L.) is a crop that could benefit from irrigation in the Northern Great Plains. Nationwide, irrigated alfalfa yields average 0.9 kg/m^2 and nonirrigated yields average 0.6 kg/m^2 (U.S. Department of Commerce, 1984). Bauder et al. (1978) measured irrigated alfalfa yields as great as 430% of dryland yields in southeastern North Dakota. Of the estimated 324 000 ha of alfalfa in North Dakota in 1993, <36 000 ha were irrigated (Anonymous, 1994).

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In spite of the potential benefits, supplemental irrigation remains underutilized in the Northern Great Plains. One reason for the lack of irrigation may be the perceived drainage limitations of many Northern Great Plains soils. This perceived drainage limitation is the result of the subsoils being labeled a "barrier". A "barrier" is a subsoil layer with hydraulic conductivity of <20% of the weighted hydraulic conductivity of the overlying strata (U.S. Department of Interior, Bureau of Reclamation, 1993), based on laboratory tests using soil cores. The laboratory tests and barrier definition have worked well in other irrigated areas, but the cores used for laboratory tests may not be large enough to adequately represent the actual soil structure (especially fractures), and resulting water flow, in many soils of the Northern Great Plains. Doering et al. (1986) showed that the standard error of hydraulic conductivity measurements with cores was more than five times greater than the standard error of hydraulic conductivity measured *in situ*. In the same study, maximum plot-measured hydraulic conductivity was 31% greater than core-measured hydraulic conductivity, even though the core-measured hydraulic conductivity was measured under saturated conditions and plot-measured hydraulic conductivity was for unsaturated conditions.

This barrier criterion is why many glacial till (or just "till") soils in the Northern Great Plains have been thought to be nonirrigable. In North and South Dakota, there are nearly 19 million ha of farm land east of the Missouri River (excluding the Red River Valley) with till-derived soils.

The objective of this study was to test the barrier criterion by determining if the subsoils restricted internal drainage at two Northern Great Plains sites considered nonirrigable using the laboratory-determined barrier criterion.

METHODS

We conducted this research at two sites in Naughton and Menoken townships of central North Dakota, approximately 50 km east of Bismarck/Mandan. Soils at the Naughton site were Falkirk loam (Fine-loamy, mixed Pachic Haploboroll) and Bowbells loam (Fine-loamy, mixed Pachic Argiboroll) (table 1). These soils developed on slope-worked alluvium deposited on till. The weathered till began at a depth of about 1 m and extended all the way to the saturated sand found at 15 m. Soils at the Menoken site were Lihen sandy loam (sandy, mixed Entic Haploboroll), Roseglen loam (fine-loamy, mixed Pachic Haploboroll), and Parshall sandy loam (coarse loamy, mixed Pachic Haploboroll) (table 1). These soils developed on aeolian-lacustrine sediments deposited over fine lacustrine sediments. There were many layers of fine sand, silt, clay, and unweathered material above the saturated material (at a depth of 13 m) at the Menoken site. The soils at both sites, especially the subsoils, were extensively fractured. Neither site normally has a water table within 13 m of the soil surface.

Eighteen plots (fig. 1), 2.5 × 2.5 m, were constructed at each site (Doering et al., 1986). A plastic barrier of 0.76 mm thickness was placed around the outside of each plot and buried to a depth of 2.3 m. Two bands of granular bentonite, about 70 mm wide, were placed inside the plastic barriers at depths of 0.6 and 1.2 m to prevent water flow along the plastic-soil interface. A frame around each plot extending about 80 mm above the soil surface prevented runoff or runon. The bottom 1 m of the 150 mm wide trench (used to place the plastic around the plot) was filled with concrete. A permanent access tube for the neutron probe was placed in the center of each plot. The tube was installed to allow monitoring to a depth of 2.7 m. For this study, soil water content was monitored to a depth of 1.8 m, approximating the alfalfa root zone. Permanent tensiometers were installed through the sides of the plots. The cups of the tensiometers were placed at depths of 0.9, 1.35, and 2.0 m. Tubing connected the tensiometers to a manometer board at the soil surface. Plot bottoms were not disturbed so the natural vertical flow characteristics of the soils were retained.

Pioneer 524 alfalfa was established in 1984 at the Menoken site and in 1986 at the Naughton site. Winterkill claimed all plots after the 1988 season so 'Vernal' alfalfa was established at both sites in 1989. Experimental treatments were not applied during establishment years.

The irrigation treatments were selected to exacerbate any problems that might develop under restricted drainage conditions, if present. The treatments were two irrigation water qualities and three water quantities in a factorial randomized complete block design with three replications. The two irrigation water qualities were: (1) EC_{iw} of 0.1 S/m and SAR_{iw} of 4, and (2) EC_{iw} of 0.34 S/m and SAR_{iw} of 16. The 0.1 S/m irrigation water was similar to or of slightly lesser quality than Missouri River water, a major water source in the area. The 0.34 S/m water had EC_{iw} and SAR_{iw} similar to the poor-quality groundwater found in the area. Our 0.34 S/m water was synthesized by adding NaCl and $CaCl_2$ to the 0.1 S/m water. The water quantities were one (1ET), two (2ET), and three (3ET) times the calculated Jensen-Haise evapotranspiration (ET) of alfalfa. Our 1ET treatment was the amount an irrigator would apply when scheduling irrigations using the checkbook method of Lundstrom and Stegman (1983). The 2ET and 3ET treatments were designed to produce overirrigated conditions. A weather station at each site recorded the climatic data (air temperature, solar radiation, and precipitation) used to calculate Jensen-Haise ET (Jensen et al., 1970) for alfalfa and the resulting irrigation amounts. Irrigation water was applied weekly, the same day each week, by flooding each plot with the calculated amount of water (such that irrigation plus precipitation was equal to one, two, or three times the calculated ET).

Table 1. Texture by depth for soils at the Menoken and Naughton sites

	Menoken Site			Naughton Site	
Depth (m)	Lihen Sandy Loam	Parshall Sandy Loam	Roseglen Loam	Falkirk Loam	Bowbells Loam
0 to 0.15	Loamy Sand	Loamy Sand	Loam	Loam	Loam
0.15 to 0.5	Sand	Sand	Loam	Silt Loam	Clay Loam
0.5 to 0.9	Sand	Sand	Silt Loam	Silt Loam	Clay Loam
0.9 to 1.2	Silty Clay	Silty Clay	Loamy Fine Sand	Silt Loam	Clay Loam
1.2 to 1.5	Silty Clay	Silty Clay	Silty Clay	Clay Loam	Clay Loam

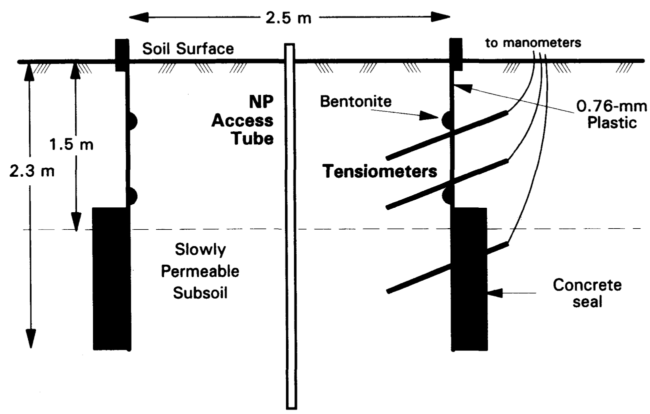

Figure 1–Schematic side view of a plot at the Menoken site including neutron probe (NP) access tube and tensiometer placement. Plots at the Naughton site were identical except for the depth to and material of the subsoil.

Soil water content and matric potential were measured weekly. We measured soil water content to a depth of 1.8 m, in 0.15 m increments, with a neutron probe. Tensiometer data were used to detect water tables and calculate the hydraulic gradients.

Internal drainage amounts were calculated with Darcy's equation:

$$q = Ki$$

where

q = water flux (mm/d)

K = hydraulic conductivity (mm/d)

i = hydraulic gradient, dimensionless

Data from the tensiometers installed at 1.35 and 2.0 m were used to calculate the hydraulic gradients. The hydraulic conductivities used in Darcy's equation were found in previous tests of the plots (Trooien and Reichman, 1990; Doering et al., 1986). Each plot had a unique hydraulic conductivity curve computed as a function of matric potential at the 2.0 m depth.

The water balance during the irrigation season is presented in this article. Stored soil water and early-season

precipitation were usually sufficient to meet crop water needs in May and June and alfalfa growth and irrigation ended in mid- to late-September. Thus, we calculated the water balance from 1 July to 1 October or the end of monitoring, whichever was earlier.

Tensiometer data used to calculate internal drainage amounts were collected weekly from the same plots; thus, they were not independent of one another. To account for the autocorrelation associated with nonindependent measures, the statistical test used was repeated measures analysis of variance, appropriate for a repeated measures complete block design (Hall, 1994; SAS, 1990). The analyses of variance were performed to reveal differences of internal drainage due to water quantity and quality treatments, blocking, and year-to-year variation. Blocking is done to make responses within a replication as uniform as possible so differences of responses will be due to the applied treatments.

RESULTS

Results of statistical tests of the internal drainage data were similar, though not identical, for the two sites (table 2). The effect of the irrigation water quantity treatments, increased drainage due to increased water application (fig. 3), was significant at both sites at the 0.01 level. Also significant at both sites was the effect of years on internal drainage amounts (table 2), reflecting the year-to-year variation of internal drainage amounts (fig. 3) resulting from the year-to-year weather variations. The year by irrigation water quantity interaction was also significant at both sites (table 2). This also was due to year-to-year weather variations.

The amount of water applied at the Naughton site was relatively consistent from year to year (fig. 2). The greatest amount was applied in 1988; the site received 136 mm precipitation and the 3ET plots received 736 mm of irrigation water, resulting in 872 mm of precipitation plus irrigation. The least amount of water was applied in 1992—142 mm of precipitation and 511 mm of irrigation for the 3ET plots.

Application of the 1ET treatment resulted in internal drainage amounts of 93 mm or less (fig. 3). Internal drainage amounts were less than zero (meaning net upward water movement) in 1987, for the 0.1 S/m water in 1988, and for the 0.34 S/m water in 1992. The greatest amount of upward water movement at the Naughton site was for the 0.1 S/m water in 1987, when 19 mm moved upward during the irrigation season. For the 2ET treatment, an average of

Table 2. F values from the repeated measures analysis of variance of the internal drainage data

Source	Naughton Site	Menoken Site
Blocks	5.35*	1.54
Water quantity	150.71†	2415.94†
Water quality	3.43	14.33†
Quantity × quality	1.64	19.73†
Year	45.20†	36.02†
Year × blocks	2.52*	0.32
Year × quantity	14.13†	12.37†
Year × quality	1.36	1.15
Year × quantity × quality	1.49	2.23*

* Significant at the 0.05 level.
† Significant at the 0.01 level

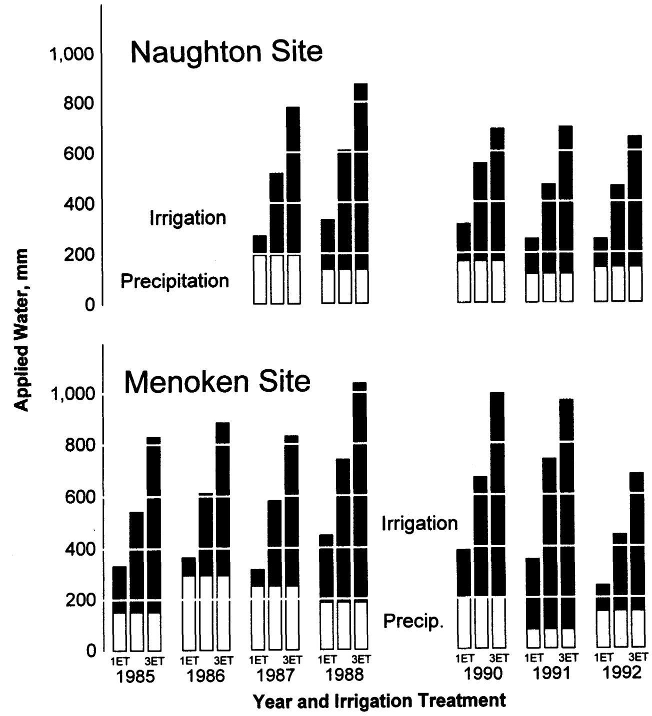

Figure 2–Average water amounts added to the plots from 1 July to the end of monitoring each year for the Naughton site and the Menoken site. The top of the irrigation bar indicates the total amount of water added (irrigation plus precipitation). For example, the precipitation at the Menoken site in 1985 was 151 mm and the irrigation water applied to the 1ET treatment was 172 mm, resulting in a total of 323 mm of water for the 1ET treatment in 1985.

109 mm (21% of the applied water) at the Naughton site drained. An average of 39% (292 mm) of the applied water drained from the root zone of the 3ET plots at the Naughton site (fig. 3). The year with the greatest internal drainage was 1990, when 555 mm drained from the 3ET treatment receiving the 0.34 S/m water.

The effects of blocking when assigning the experimental treatments and the year-by-block interaction were significant at the Naughton site (table 2). The interaction of blocks with water quantity treatment was also significant. The effects of irrigation water quality, and all of its interactions, were not significant at the Naughton site.

Water applications at the Menoken site were more variable among years (fig. 2). The year of greatest application was 1988; 851 mm of irrigation water were applied to the 3ET plots (irrigation plus precipitation was 1 037 mm). The least amount of water was applied in 1992, when 532 mm of irrigation water were applied to the 3ET plots at the Menoken site (when irrigation plus precipitation was 678 mm).

Internal drainage amounts from the 1ET treatments at the Menoken site were small: 42 mm or less (fig. 3). For the 2ET treatment and the plots receiving the 0.1 S/m water, an average of 24% (149 mm) of the applied water drained at the Menoken site. For the plots receiving the 0.34 S/m water, the internal drainage averaged 38% (230 mm) of the applied water for the Menoken site. The average amount of internal drainage from the 3ET treatments was 66% (585 mm) of the applied water for the 0.1 S/m water and 63% (562 mm) for the 0.34 S/m

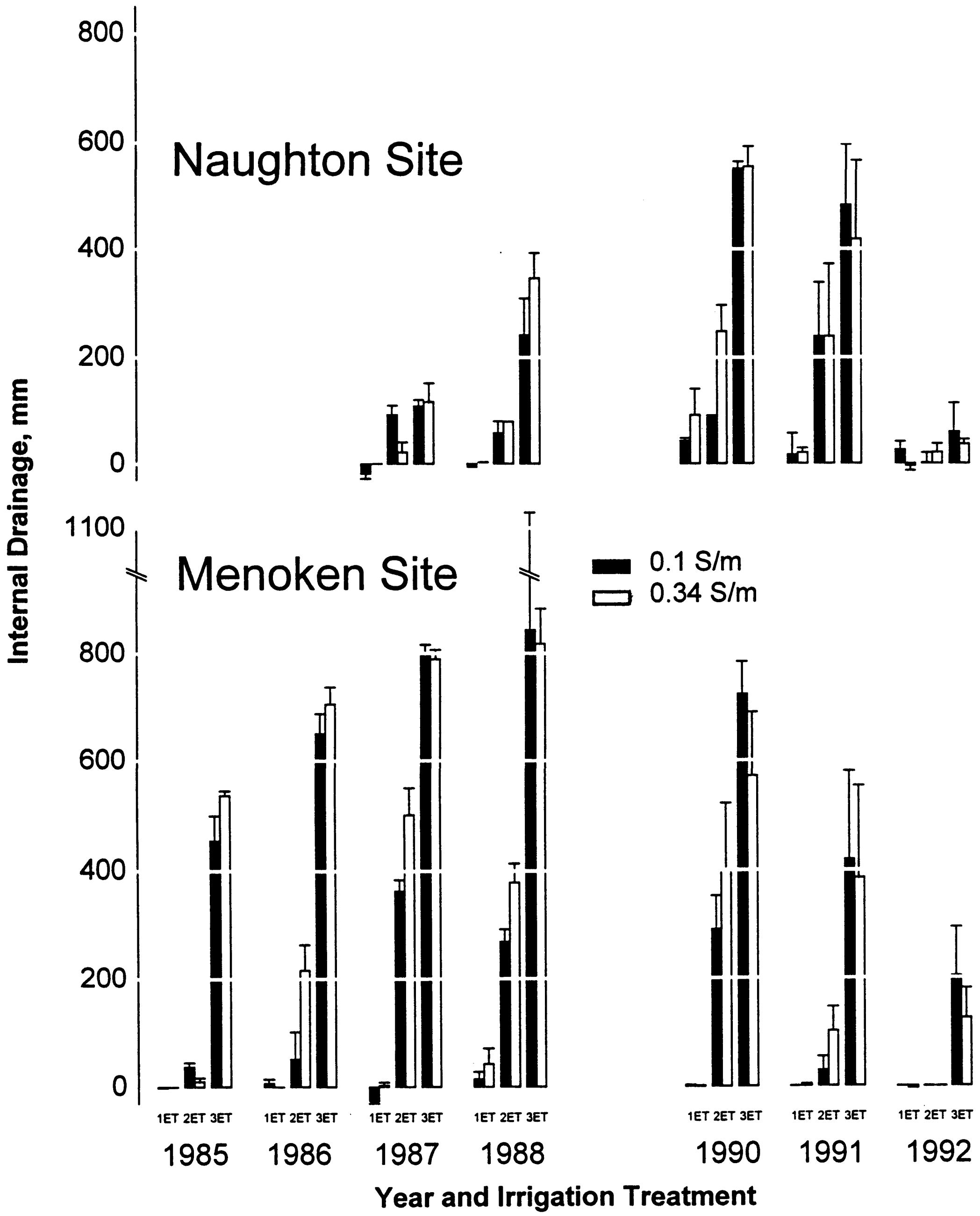

Figure 3–Internal drainage amounts averaged for the three replicates of each treatment for the Naughton site and Menoken site. The distance from the end of the filled bar to the error marker indicates the standard error of the three replicates.

irrigation water. The greatest single-season internal drainage amount was 843 mm for the 3ET treatment and 0.1 S/m water at the Menoken site in 1988.

The effects of the water quality treatments and the water quality by quantity interaction at the Menoken site were significant. More water drained from the plots receiving the 0.34 S/m irrigation water for the 1ET and 2ET treatments, but the effect was reversed most years for the 3ET treatment. This change of response to irrigation water salinity for the 3ET plots at the Menoken site caused the irrigation water quantity by quality and the year by quantity by quality interactions to be significant at the Menoken site (table 2). Block effects were not significant at the Menoken site.

Application of the 3ET treatment maintained water contents at or near field capacity (fig. 4). The field capacity values shown in the figure are measured soil water contents after three days of drainage from a saturated soil profile. The 1ET treatment was not sufficient to maintain a wet root zone throughout the irrigation season and the water content was gradually depleted through the irrigation season (fig. 4). The crop ET was greater than the ET calculated for irrigation scheduling, resulting in depletion of stored soil water. The difference of ET was due to the "small plot" effect—the elevation of ET due to insufficient fetch surrounding the plots. The 2ET treatment maintained a root zone water content between the 1ET and 3ET treatments (fig. 4). During many years, the water content in the 2ET

treatment remained near field capacity throughout the irrigation season (data not shown).

Even with water contents as high as those maintained in the 3ET plots (fig. 4), a persistent water table that might impede root function was not detected by tensiometers (fig. 5). The data shown are from the Naughton site in 1991; other years were similar. The only water table detected during 1991 at the Naughton was in early July in the 1ET, 0.1 S/m treatments at the 2.0 m depth.

Finally, as a indication of the ability of the soils to drain water, the amounts drained from the 3ET plots were greater than the total amounts of water applied to the 1ET plots for every year except 1992 at the Menoken site. The same relationship (3ET internal drainage was greater than 1ET application) held true for three (1988, 1990, and 1991) of the five years for the plots receiving 0.34 S/m water at the Naughton site.

Discussion

Internal drainage amounts in 1992 were small (fig 3). The conditions in 1992 were good for alfalfa, producing yields up to 150% greater than yields in 1990 or 1991 at the Menoken site and 30% greater at the Naughton site (unpublished data). The greater yields required greater water use, leaving less water in the soil profile to drain. In addition, the amount of water applied in 1992 was less than in any other year. This difference is especially noticeable at the Menoken site (fig. 2). Less water applied and more water used also account for the fact that the internal drainage from the 3ET plots was not greater than the amount of water applied to the 1ET plots at both sites in 1992.

Irrigating when there is insufficient drainage may cause the formation of a perched water table. A water table too close to the soil surface can impede crop root functions and reduce crop yield. Optimum water table depths for maximum alfalfa yield range from 1.5 m (Benz et al., 1983) to 0.61 m (Tovey, 1963). Yield reductions have been reported for water table depths of 0.46 m (Benz et al., 1983) or 0.45 and 0.75 m (Buscaglia et al., 1994). In this study, we detected no persistent perched water tables that might decrease alfalfa yields.

In addition to perched water table formation, another hazard due to insufficient drainage capacity is salt accumulation in the root zone. A favorable root-zone salt balance must be maintained by leaching salts at least occasionally. Such leaching can be accomplished with

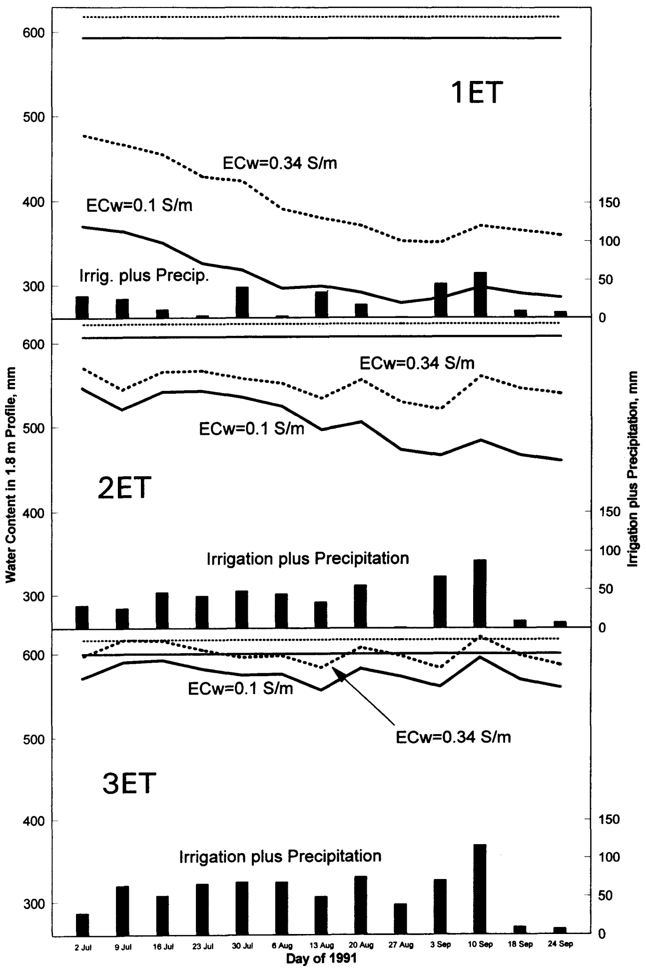

Figure 4–Soil water content in the 1.8 m profile. Data shown are for the Naughton site in 1991. The straight horizontal lines show the average field capacity by treatment. The vertical bars show weekly sums of precipitation and irrigation.

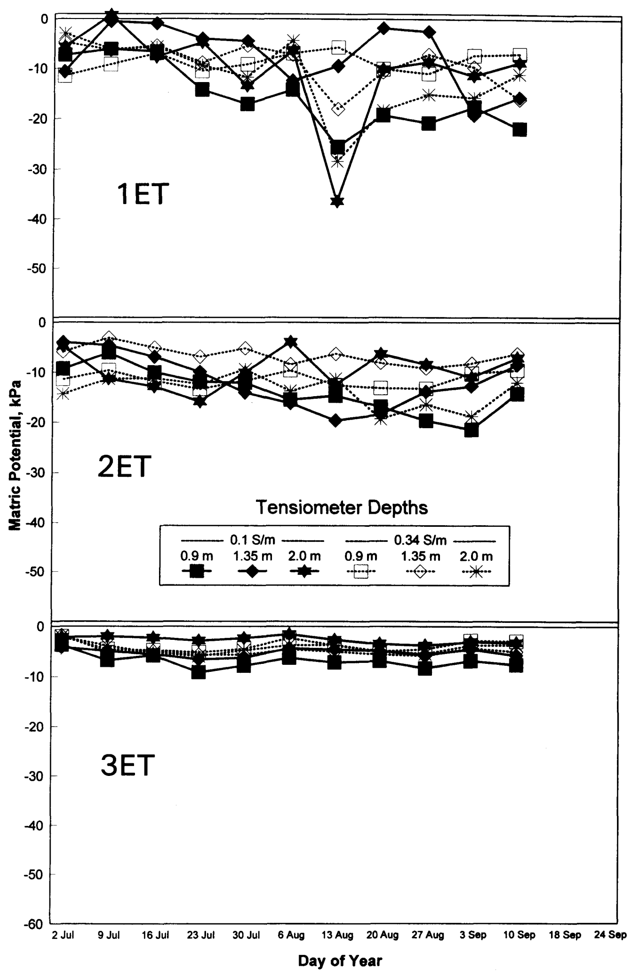

Figure 5–Measured matric potentials at the Naughton site in 1991 at the three measurement depths (0.9, 1.35, and 2.0 m). A matric potential greater than or equal to zero indicates saturated conditions (a water table).

either irrigation or precipitation in excess of crop requirements. In addition to the measured internal drainage presented here, snowmelt and early-season precipitation in excess of ET (after the soil profile is full) can be especially effective for salt leaching. The treatments we applied to the alfalfa plots were sufficient to prevent yield-reducing salt accumulations (Wienhold and Trooien, unpublished data).

Considering either the 1ET or 2ET treatment, the average drainage during this study period was greater from the plots receiving the 0.34 S/m water than from the plots receiving the 0.1 S/m water (fig. 3). This effect was observed at both sites, but was statistically significant only at the Menoken site. As the salinity in the irrigation water reduced the osmotic potential in the root zone of the 1ET and 2ET treatments, the plant was able to take up less water; more water was then left in the root zone to drain. The consistently high water content in the 3ET plots (fig. 4) overshadowed any salinity effects.

At our Naughton site, leachate will probably reach the saturated sand at 15 m because of the relative uniformity of the weathered till to that depth. However, till is a particularly variable material and one should not assume that all till landscapes will drain water equally well. A particular concern is depth to unweathered till because of its low permeability. In this article, we have explored the movement of water through weathered till. Further research is required to apply this knowledge of weathered till to the movement of water within the entire till landscape including unweathered till and lateral water movement.

Conclusions

Our data show that the top 2.3 m of the soil profile at these two sites will not impede water movement enough to preclude irrigation. The internal drainage capacity of the tested soils was great enough to allow supplemental irrigation with as much as three times the calculated alfalfa ET amount. Although the 3ET treatments maintained soil water contents at or near field capacity for the entire irrigation season, a persistent perched water table was not detected by tensiometers placed at depths of 0.9, 1.35, and 2.0 m.

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