EQUATIONS FOR DRAINAGE COMPONENT OF THE FIELD WATER BALANCE

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ABSTRACT. *Accurate estimates of the drainage component of the field water balance are needed to achieve improved management of drainage in irrigated crop production systems and obtain improved estimates of evapotranspiration (ET) from soil water measurements. Estimating drainage for numerous soil and field conditions necessitates the use of simple, yet accurate, drainage equations containing easily measured parameters. The Wilcox drainage model is a relatively simple mathematical equation with a high degree of accuracy and applicability to field conditions. Our objectives were to develop Wilcox-type drainage rate equations for three coarse-textured soils of the west-central Great Plains and assemble previously determined, but fragmented, Wilcox-type drainage equations and supporting information for three medium-textured soils of the region. Drainage plots for collection of data for development of Wilcox-type drainage equations were established on two coarse-textured soil profiles in 2008 near Garden City, Kansas. Total water content of the soil profiles was measured over time during ~48-day drainage events. Total water was plotted against drainage time on log-log scales, and the linear regression equation relating the two variables was determined. These linear equations of profile water (log_{10}) vs. drainage time (log_{10}) were used to develop Wilcox-type drainage equations in which drainage rate (dW/dT in mm/day) is expressed as a function of soil profile water content (in mm). Drainage rate equations in this article can be used to estimate the drainage component of the field water balance for improved irrigation water management and more accurate estimates of ET from soil water measurements.*

Keywords. *Field water balance, Profile drainage, Wilcox-type drainage equation, Soil water storage, Water management.*

The primary objective of irrigation water management is to provide water to achieve maximum attainable crop production while minimizing deep percolation (internal drainage) (Martin et al., 1991). Despite its importance in water management, internal drainage from the root zone is a component of the field water balance that is seldom measured adequately (Hillel, 1990). This is not surprising considering that drainage is the component of the field water balance that is most difficult to measure or calculate (Jury and Horton, 2004). In both dryland and irrigated environments, estimation of the rate and quantity of drainage is essential for accurate application of the field water balance. The inability to distinguish between profile water loss by evapotranspiration (ET) and drainage is a major problem when using soil water measurements to obtain estimates of ET (McGowan and Williams, 1980).

Submitted for review in May 2010 as manuscript number SW 8579; approved for publication by the Soil & Water Division of ASABE in February 2011.

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Internal drainage (or redistribution) is continual and shows no sharp changes or static levels, and in the absence of a water table, the drainage process continues indefinitely, albeit at a decreasing rate (Ahuja and Nielsen, 1990). Profile drainage rates of a few millimeters per day have been observed in deep dryland soils with matric potential as low as -0.06 MPa (Baver et al., 1972). Profile drainage of a Ulysses silt loam (fine-silty, mixed, superactive, mesic Aridic Haplustolls) was shown to be a measurable water loss component with profile water content at 60% of available water capacity (AWC) and greater, with drainage increasing as water increased above 60% of AWC (Stone et al., 2008). Agreement between Baver et al. (1972) and Stone et al. (2008) is shown by the fact that at -0.06-MPa matric potential the Ulysses soil had water content at ~65% of AWC (Stone et al., 1987). Research by Nielsen and Vigil (2010) and several studies cited by Peterson and Westfall (2004) showed decreased efficiency of water storage in the later portion of the fallow phase of dryland crop rotations, with efficiency likely being decreased by increased drainage from the wetter soil profiles of the later portion of fallow. The association between extensive use of fallow and formation of saline seeps in the northern Great Plains is indicative of water drainage from soil profiles during later stages of long fallow phases (Halvorson and Black, 1974; Brun and Worcester, 1975).

Accurate estimates of the drainage component of the field soil water balance are needed to achieve improved management of drainage in irrigated crop production systems and obtain improved estimates of crop water use from soil water measurements. Estimating drainage for numerous soil types and field conditions necessitates the use of simple, yet accurate, drainage equations that contain easily measured parameters (Sisson et al., 1980). The Wilcox drainage model

(Wilcox, 1959), as discussed by Sisson et al. (1980), is a relatively simple mathematical equation with a high degree of accuracy and applicability to field conditions.

Our objectives in this study were: (1) develop Wilcox-type drainage rate equations for three coarse-textured soils of the west-central Great Plains and (2) assemble previously determined, but fragmented, Wilcox-type drainage rate equations and supporting information for three medium-textured soils of the region.

Background of Drainage Rate Equations

Richards et al. (1956) measured soil water content over time during 59 days of drainage following deep irrigation of a fine sandy loam profile free of plants and with evaporation. When plotted on log-log scales, the relationship between total water and drainage time was linear and could be expressed by the equation:

$$W = aT^{b} \quad (1)$$

where W is the equivalent depth of water in a soil profile, T is drainage time, a is water amount (W) at T = 1, and b is the slope of W vs. T plotted in log-log scales. Differentiating equation 1 with respect to T yields:

$$dW/dT = abT^{(b-1)} \quad (2)$$

where a and b are constants for a given soil profile, and drainage rate (dW/dT) is expressed as a function of time (T) (Richards et al., 1956). In a continuation of the work by Richards et al. (1956), Ogata and Richards (1957) measured water content during drainage following deep irrigation with the soil surface sealed from evaporation. Ogata and Richards (1957) found that profile water amount and drainage time were linearly related when plotted on log-log scales, confirming the findings of Richards et al. (1956).

Wilcox (1959) measured soil water content and drainage time during 12 drainage tests with bare soils that had been irrigated to fill the soil profile and covered to prevent evaporation. Relationships between profile water content and drainage time were linear when plotted on log-log scales (Wilcox, 1959), supporting the findings of Richards et al. (1956) and Ogata and Richards (1957). Some drainage time is required following complete profile wetting (from ~1 day on coarser-textured soils up to 2 to 3 days on finer-textured soils) before the water amount vs. time data will fit a linear log-log plot (Wilcox, 1959; Sisson et al., 1980). Wilcox (1959) proposed that drainage rate be expressed as a function of profile water content instead of relating drainage rate to drainage time as in equation 2. Rearranging equation 1 per Wilcox (1959) yields:

$$T = (W/a)^{1/b} \quad (3)$$

Substituting equation 3 into equation 2 yields:

$$dW/dT = ab(W/a)^{(b-1)/b} \quad (4)$$

where drainage rate (dW/dT) is expressed as a function of profile water content (W) as suggested by Wilcox (1959).

Estimating drainage rate with equation 4 was useful in estimating drainage from soil profiles and was referred to as the Wilcox method by Miller and Aarstad (1972). In Australia, Aston and Dunin (1977) found that agreement between computed (Wilcox method) and measured soil water drainage over 5 years was good and concluded the Wilcox method was appropriate for describing drainage from soil under field conditions. Sisson et al. (1980) discussed the Wilcox (1959) modification of the original Richards et al. (1956) equation by expressing drainage rate at a specific depth as a function of total water above that depth. They concluded from their examination of models for estimating drainage from field plots that the resulting expression (eq. 4) was useful in accurately estimating drainage from soil profiles.

Drainage Plot Data Collection

Field plots for determination of Wilcox drainage equations were established in 2008 on two coarse-textured soil profiles located 245 m apart on a near north-south line on the slope (37° 56′ N; 100° 49′ W) immediately south of the Arkansas River near Garden City, Kansas. The two soil surfaces were at elevations 18 m above (north plot) and 22 m above (south plot) the riverbed (850 m above sea level). Soils of the immediate study area are coarse-textured, deep, and excessively drained, having formed in sandy eolian sediments that overlie terrace gravels in a broad band along the south side of the river valley (Harner et al., 1965). The soils previously were mapped (Harner et al., 1965) as Tivoli fine sands (mixed, thermic Typic Ustipsamments), but are now classified (Soil Survey Staff, NRCS-USDA, 2010) as Valent fine sands (mixed, mesic Ustic Torripsamments).

Drainage plots were level, vegetation-free areas of 13.2 m^2 (3.63 × 3.63 m). Vertical boards 0.30 m tall were installed around the perimeter of each plot to retain water ponded on the soil surface. Four aluminum access tubes (38 mm in diameter and 2.9 m long) were installed in each of the two drainage plots; one tube was placed at each of the four corners of the center 0.92- × 0.92-m plot area. Three tensiometers were installed 1.9 m deep in the center 0.3- × 0.3-m area of each drainage plot. Drainage plots were ponded with water to achieve thorough wetting of the 2.44-m soil profile prior to drainage measurements. Steady-state infiltration rates during ponding were 13 cm/h (north plot) and 19 cm/h (south plot). Tensiometers, read only during ponding, were used to gauge profile wetting. Ponding was maintained for 2 h after tensiometers at the 1.9-m depth had reached equilibrium at matric potential of near zero. The supply of water was then stopped and water remaining on the surface was allowed to infiltrate. As soon as standing water disappeared from the surface, plots were covered with black polyethylene sheeting to prevent evaporation during the drainage period. The sheeting was pierced so tensiometers and neutron probe access tubes could protrude. The time when standing water left the soil surface was designated as zero drainage time and soil water was measured during ~48 days of drainage. Soil water data collected 1 h after zero drainage time by neutron probe confirmed that thorough wetting through the 2.44-m profile depth had been achieved. Coated vinyl tarps (4.9 × 4.9 m) were maintained over the drainage plots to deflect rain from plots.

Volumetric water content in the drainage plots was monitored with a neutron probe (Model 503DR, CPN International, Inc., Martinez, Calif.). The neutron probe was field calibrated with gravimetric water content and dry bulk density determined from soil samples centered at 0.305-m depth increments from the 0.15-m through 2.29-m soil profile depths. Gravimetric water content soil samples (15.24 cm long and 3.81 cm diameter) were collected with a hydraulic probe. Bulk density soil cores (6.75 cm long and 3.43 cm diameter) were collected with a Madera probe (Precision Machine Co., Inc., Lincoln, Nebr.) as described by Evett (2007). Because of gravel below the 1.5-m soil depth in the north plot, bulk density of the three deepest north-plot depths was determined from soil samples collected with a 6.79-cm internal diameter sampling barrel and hydraulic probe, not the Madera probe. Volumetric water content for neutron probe calibration was calculated as gravimetric water content multiplied by dry bulk density for the specific profile depth. A linear regression equation was developed by using PROC GLM of SAS (version 9.1, SAS Institute Inc., Cary, N.C.) with volumetric water content the dependent (Y) variable and count ratio (soil reading count divided by standard count) the independent (X) variable. The developed equation was:

$$Y = -0.0200 + 0.1709X \qquad (5)$$

where sample size (n) = 72, coefficient of simple determination (r^2) = 0.849, and root mean square error (RMSE) = 0.014 m^3/m^3. Neutron probe readings were taken periodically over time during the 48 days of drainage, more frequently at earlier and less frequently at later drainage times, at soil depths of 0.15 m through 2.29 m in 0.305-m depth increments. Total water of the 1.52-, 1.83-, and 2.44-m soil profiles was calculated as 305 mm times volumetric water content measured at individual depths and summed over the respective total profile depth.

Particle size distribution and water content at -1.5-MPa matric potential were determined with composited soil samples collected from the eight profile depths during gravimetric water content determination. Particle size distribution was determined by hydrometer and sieving (Gee and Or, 2002). Sample mass was 80 g, sodium hexametaphosphate was the dispersing chemical, and corrected hydrometer readings at the 8-h settling time represented clay content. Sediment and suspension were poured through sieves with openings of 2.0 and 0.053 mm, and the oven-dry mass of material retained represented sand (0.053 to 2.0 mm) and gravel (>2.0 mm). Silt content was calculated as oven-dry sample mass minus the mass of clay plus sand plus gravel. Water content at -1.5-MPa matric potential was determined with a cellulose acetate membrane system (Klute, 1986). Particle size distribution was determined on three subsamples (runs), and water content at -1.5 MPa was determined on five subsamples (runs); means from the multiple runs are reported.

Results and Discussion

Soil physical properties of the two Garden City drainage plots are presented in table 1. The north plot (table 1a) had >13% by mass of gravel below the 1.5-m soil profile depth. The south plot (table 1b) had gravel content of <2% by mass at all soil depths. Both plots had clay content of >3% to <5% by mass in the upper 1.2 m of the soil profile. Below the 1.5-m profile depth, clay content was ≥7% by mass in the south plot (table 1b) and <2% by mass in the north plot (table 1a). Dry bulk density by depth ranged from 1.60 to 1.73 g/cm^3 in the north plot (table 1a) and from 1.48 to 1.63 g/cm^3 in the south plot (table 1b). Water adsorbed and held at -1.5-MPa matric potential is positively correlated with specific surface of soil material. Therefore, water content at -1.5 MPa was greater at soil depths having greater clay concentration (table 1). Below the 1.5-m soil profile depth, water held at -1.5 MPa was <0.01 g/g in the north plot (table 1a) with clay content <2% by mass; in the south plot (table 1b), water held at -1.5 MPa was slightly >0.03 g/g (clay content ≥7% by mass).

Table 1. Descriptive physical properties (texture, density, and water content at -1.5-MPa matric potential) at eight centering depths within two Valent fine sand soil profiles near Garden City, Kans.

Soil Depth (m)	Gravel, >2.0 mm (g/kg)	Sand, 0.053 to 2.0 mm (g/kg)	Silt, 0.002 to 0.053 mm (g/kg)	Clay, <0.002 mm (g/kg)	Dry Bulk Density (g/cm^3)	Water Content at -1.5 MPa (g/g)
(a) Valent fine sand (gravelly below 1.5 m) (North plot)						
0.15	7	904	53	36	1.62	0.0238
0.46	10	889	57	44	1.60	0.0238
0.76	25	883	44	48	1.63	0.0215
1.07	57	878	29	36	1.67	0.0131
1.37	71	891	18	20	1.65	0.0097
1.68	135	825	23	17	1.73	0.0076
1.98	220	738	26	16	1.73	0.0078
2.29	148	812	25	15	1.73	0.0078
(b) Valent fine sand (South plot)						
0.15	1	942	17	40	1.56	0.0211
0.46	0	955	10	35	1.54	0.0168
0.76	0	959	5	36	1.48	0.0167
1.07	1	956	9	34	1.58	0.0167
1.37	11	924	19	46	1.63	0.0202
1.68	5	881	43	71	1.57	0.0342
1.98	5	840	84	71	1.58	0.0325
2.29	2	843	85	70	1.52	0.0312

Total water content of the two 1.83-m Valent fine sand profiles was measured over time during the ~7-week drainage events and is shown in figure 1. Watts (1975) graphically presented total water and available water vs. time during drainage as well as soil water content at -1.5 MPa matric potential for a 1.5-m profile of Valentine loamy sand (mixed, mesic Typic Ustipsamments) and these data were used in a soil-water-nitrogen model for irrigated corn (*Zea mays* L.) (Watts and Hanks, 1978). From the graphed data of Watts (1975), total water was determined for the 1.5-m soil profile and then extrapolated to a profile depth of 1.83 m by assuming a continuation of similar soil properties with depth and by multiplying total water for 1.5 m by 1.22. Total water of the 1.83-m Valentine soil profile was graphed versus time for an ~3-week drainage event and is shown in figure 2. Stone et al. (1994) plotted total water of 1.83-m profiles of Keith (fine-silty, mixed, superactive, mesic Aridic Argiustolls), Richfield (fine, smectitic, mesic Aridic Argiustolls), and Ulysses silt loam soils against time during long-term drainage events. Because total water over time during drainage was graphed for the Keith, Richfield, and Ulysses soils by Stone et al. (1994), those plots are not repeated in this article.

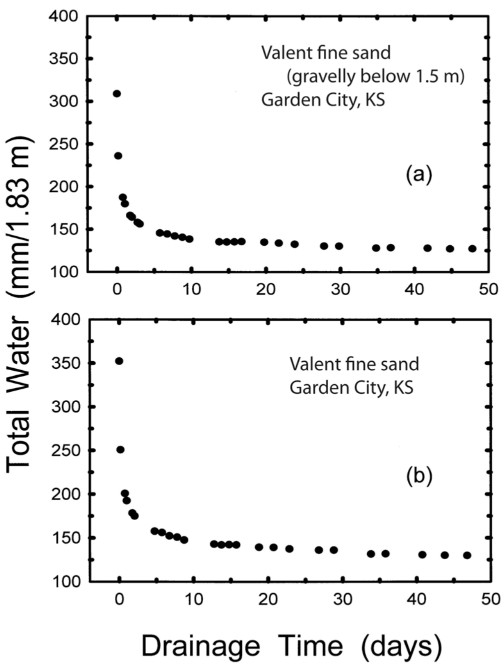

Figure 1. Total water vs. drainage time of 1.83-m profiles of (a) Valent fine sand (gravelly below 1.5 m) and (b) Valent fine sand located near Garden City, Kans.

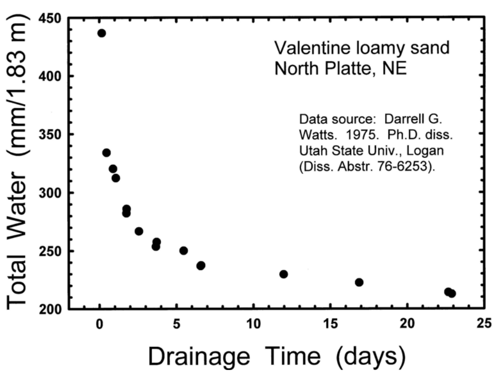

Figure 2. Total water vs. drainage time of Valentine loamy sand (1.83-m profile) located near North Platte, Nebr. Data are from Watts (1975).

Depending on objectives and conditions of soil water balance research activities, different profile depths are appropriate for use in estimating the water drainage component. For example, the 1.52-m soil profile depth version of the Wilcox-type drainage equation for Keith silt loam was used by O'Brien et al. (2001) and Lamm et al. (2007), the 1.83-m profile depth version for Ulysses silt loam was used by Stone et al. (2008), and 2.44-m profile depth versions were used by Caldwell et al. (1994) (Richfield silt loam) and Lamm et al. (1995) (Keith silt loam). Therefore, we developed total water vs. drainage time similar to that shown for the 1.83-m profile depth in figures 1 and 2 also for the 1.52- and 2.44-m soil profile depths (graphed data not shown in this article).

Total water of soil profiles was plotted against drainage time on $\log_{10}$ versus $\log_{10}$ scales, and simple linear regression was performed by using PROC GLM of SAS (version 9.1, SAS Institute Inc., Cary, N.C.) to develop the equation that relates the two variables. Total water of the 1.83-m profile ($\log_{10}$ scale) versus drainage time ($\log_{10}$ scale) is presented in figure 3 for the Valent fine sand (gravelly) (section a) and the Valent fine sand (section b) soils and in figure 4 for the Valentine soil. Similar graphs with derived linear equations for Keith, Richfield, and Ulysses soils are presented in Khan (1996) and are not repeated in this article.

From the linear equations involving log-log plots of profile water in millimeters and drainage time in days,

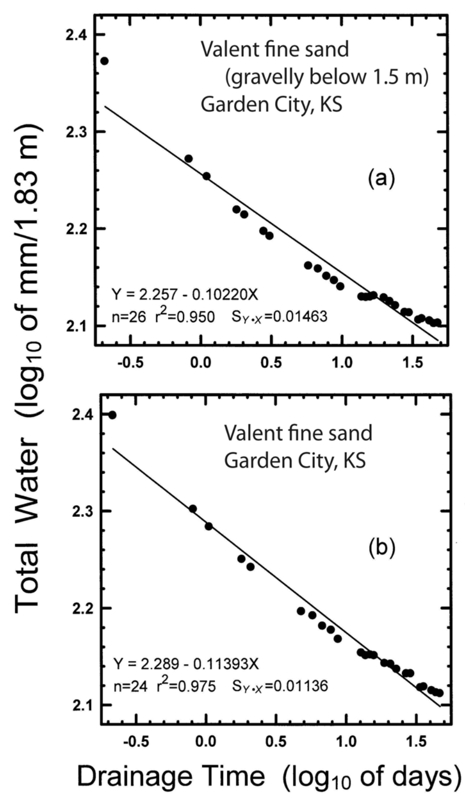

Figure 3. Total water ($\log_{10}$ scale) vs. drainage time ($\log_{10}$ scale) of 1.83-m profiles of (a) Valent fine sand (gravelly below 1.5 m) and (b) Valent fine sand located near Garden City, Kans. Results shown are from linear regression analyses.

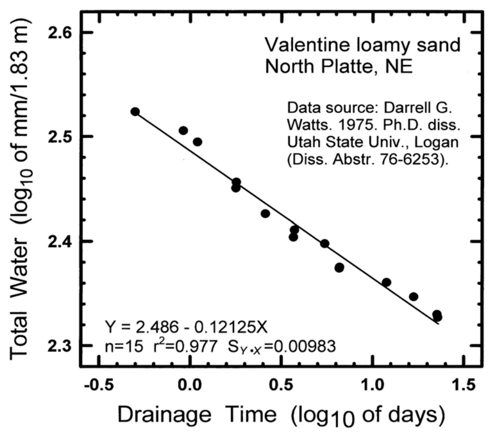

Figure 4. Total water ($\log_{10}$ scale) vs. drainage time ($\log_{10}$ scale) of Valentine loamy sand (1.83-m profile) located near North Platte, Nebr. Results shown are from linear regression analysis. Data are from Watts (1975).

Wilcox-type drainage rate equations were developed by using equation 4, with dW/dT being drainage rate in millimeters/day. The variable W in equation 4 is total water content of the soil profile in millimeters, and constants a and b are total water at 1 day and slope of water content vs. time from the linear equation of log-log data, respectively. The drainage rate equations for soil profiles of 1.52-, 1.83-, and 2.44-m depth, along with the profile total water contents at the drained upper limit and at -1.5 MPa matric potential, are presented in table 2. Total profile water at -1.5 MPa shown in table 2 was calculated from data of table 1 for the two Valent soils, graphical data of Watts (1975) for the Valentine soil, tabular data of Stone et al. (1987) for the Ulysses soil, and tabular data of Darusman (1994) for the Keith and Richfield soils. Water content at -1.5 MPa establishes an estimate of the lower limit of soil water availability. There are reported instances where field-measured profile water was less than that held at -1.5 MPa. For example, the 1.83-m profile of Ulysses silt loam in table 2 contains 332 mm total water at -1.5 MPa, whereas profile water measured at harvest after dry seasons was 290 mm (Stone et al., 1987).

Drained upper limit water content values were estimated as the location of primary slope change in the graphed data of figure 1 (Garden City location) and figure 2 (data of Watts, 1975) and from similar graphs for the three silt loam soils of Stone et al. (1994). The drained upper limit water contents of 660, 642, 650, 282, 190, and 178 mm (table 2) were reached after 5.8, 6.1, 7.1, 2.0, 1.2, and 1.2 days of drainage for the 1.83-m profiles of Keith, Richfield, Ulysses, Valentine, Valent, and Valent (gravelly) soils, respectively. These lengths of drainage time for reaching field-determined drained upper limit water capacity values were not unexpected. Working with 61 field soil profiles from 15 states of the United States, Ratliff et al. (1983) found that 2 to 12 days of drainage usually were required for soils to reach the drained upper limit water content, and some fine-textured soils with restrictive layers required up to 20 days of drainage.

Summary and Conclusions

We developed Wilcox-type drainage rate equations for two coarse-textured soils (Valent and Valentine series) of the west-central Great Plains and assembled information from various sources on the Wilcox-type drainage equations for three medium-textured soils (Keith, Richfield, and Ulysses series) of the region. The drainage rate equations can be used

Table 2. The developed Wilcox drainage equations and upper (water content at drained upper limit) and lower (water content at -1.5 MPa) bounds of available water capacity for three profile depths of six soils of the west-central Great Plains (sans the 2.44-m profile of the Ulysses and Valentine soils).

Soil	Location	Wilcox Drainage Equation[a]	Water at DUL[b] (mm/profile)	Water at -1.5 MPa (mm/profile)
(a) 1.52-m deep soil profiles				
Keith sil[c]	Colby, Kans.	$dW/dT = -24.5(W/598)^{25.39}$	557	274
Richfield sil	Holcomb, Kans.	$dW/dT = -21.0(W/573)^{28.25}$	536	273
Valent fs	Garden City, Kans.	$dW/dT = -17.4(W/148)^{9.50}$	144	44
Valent fs (gravelly below 1.5 m)	Garden City, Kans.	$dW/dT = -15.0(W/156)^{11.34}$	153	46
Ulysses sil	Tribune, Kans.	$dW/dT = -32.7(W/604)^{19.47}$	543	288
Valentine ls	North Platte, Nebr.	$dW/dT = -30.9(W/255)^{9.25}$	235	65
(b) 1.83-m deep soil profiles				
Keith sil	Colby, Kans.	$dW/dT = -32.2(W/715)^{23.17}$	660	313
Richfield sil	Holcomb, Kans.	$dW/dT = -27.5(W/690)^{26.06}$	642	316
Valent fs	Garden City, Kans.	$dW/dT = -22.2(W/195)^{9.78}$	190	60
Valent fs (gravelly below 1.5 m)	Garden City, Kans.	$dW/dT = -18.5(W/181)^{10.79}$	178	50
Ulysses sil	Tribune, Kans.	$dW/dT = -42.7(W/729)^{18.06}$	650	332
Valentine ls	North Platte, Nebr.	$dW/dT = -37.1(W/306)^{9.25}$	282	78
(c) 2.44-m deep soil profiles				
Keith sil	Colby, Kans.	$dW/dT = -50.0(W/946)^{19.94}$	862	388
Richfield sil	Holcomb, Kans.	$dW/dT = -40.1(W/920)^{23.94}$	850	402
Valent fs	Garden City, Kans.	$dW/dT = -33.6(W/303)^{10.03}$	296	90
Valent fs (gravelly below 1.5 m)	Garden City, Kans.	$dW/dT = -27.4(W/242)^{9.84}$	238	58

[a] dW/dT is drainage rate in millimeters per day and W is profile water content in millimeters.
[b] DUL = drained upper limit.
[c] Soil textures represented as sil (silt loam), fs (fine sand), and ls (loamy sand).

to simulate drainage conditions of irrigated cropping systems and partition soil water measurements into ET and drainage components. The equations can be used to extend to multiple locations and soils the simulation of drainage for the field water balance that is used in developing yield versus water supply relationships of the principal crops of the west-central Great Plains, as used by Stone et al. (2006). The yield versus water supply results could then be used to expand the application and usefulness of software developed to provide for improved water management and conservation, such as the water allocation software developed by Klocke et al. (2006). The Klocke et al. (2006) software involves a database of one soil and one weather data file (location), but the drainage rate equations of this report will allow software expansion to include multiple soils and locations.

Acknowledgement

This work was supported in part by funds from the USDA-CSREES under Award no. 2008-34296-19114 and the Ogallala Aquifer Project of the USDA-ARS under Agreement no. 58-6209-6-031. Contribution 10-276-J from the Kansas Agricultural Experiment Station.

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