Published online May 17, 2007

Original Research

Vadose Zone Journal

Neutron Moisture Meter Calibration in Six Soils of Uzbekistan Affected by Carbonate Accumulation

Steven Evett,* Nazirbay Ibragimov, Bakhtiyor Kamilov, Yusupbek Esanbekov, Makhsud Sarimsakov, Jamaliddin Shadmanov, Rahmonkul Mirhashimov, Ruzibay Musaev, Tilak Radjabov, and Bahram Muhammadiev

Improvements in water use efficiency of the irrigated agriculture of Uzbekistan begin with determination of crop water use under its different climates, soils, and management practices. The neutron moisture meter (NMM) is a key tool for determination of crop water use, which we define here as being equal to transpiration and evaporation from the soil surface, i.e., the evapotranspiration. We accurately field calibrated NMMs at six locations in Uzbekistan, in soils ranging from deep, uniform silt loams of loessial origin to highly stratified alluvial soils near the Amu Darya River. In all soils, separate calibrations were found for the 10-cm depth due to closeness to the soil–air interface. Near Tashkent and at the Syrdarya Branch Station, the soil below 10 cm was divided into two layers based on the increased $CaCO_3$ content in the lower of the two layers. Distinctly different calibration equation slopes were found for these layers. At the Kashkadarya Branch Station, a single calibration was sufficient for the soil below 10 cm. At the Khorezm Branch Station, an abrupt change in soil texture at the 90-cm depth required separate calibration equations for the 30- to 70-cm depth range (silt loam) and the 110- to 170-cm depth range (fine sand). Overall, the root mean square errors (RMSEs) of calibration ranged from 0.009 to 0.025 $m^3 m^{-3}$ and r^2 values ranged from 0.91 to 0.99. Data gathered provide an excellent illustration of why calibration efforts should organize soil water content data by depth range. Two examples of profile water content measurement for crop water use studies are given.

Abbreviations: ET, evapotranspiration; NMM, neutron moisture meter; RMSE, root mean square error; UNCGRI, Uzbek National Cotton Growing Research Institute.

Irrigation in Central Asia is important to the economy and ecology of the region. In Uzbekistan, 60 to 65% of the gross national income is from agriculture, and cotton (*Gossypium hirsutum* L.) production makes up about 50% of the gross national income. This nation of 26 million people encompasses 447,000 km^2, about half of which is desert. Uzbekistan irrigates 4.3 million ha of land, much of which is in the wide floodplains of the Syr Darya and Amu Darya rivers, which are subject to periodic high water tables and soil salinization. Cotton and wheat (*Triticum aestivum* L.) are major crops in the country, followed by maize (*Zea mays* L.), vegetables, and fruits. Due to its deep continental geographic location, the country's precipitation is small and erratic. Thus, agricultural production in the country, as in all of Central Asia, is largely based on irrigation, and irrigation water supply is the first factor limiting crop yield in the region. Large-scale irrigation has reduced flow in the river systems, causing the Aral Sea to shrink and contributing to the creation of an ecological crisis zone around the sea.

Land under irrigated agriculture in the Republic of Uzbekistan is entirely clean tilled at present (moldboard plow and disk, followed by toothed harrow). Mirzajanov (1981b) reported that 1,941,000 ha of irrigated land are influenced by wind erosion (deflation) and around 561,000 ha are influenced by irrigation erosion. Mirzajanov (1981a) also stated that of the arable land that is influenced by wind erosion, erosion is low on 375,000 ha, medium to moderate on 2,030,000 ha, and high on 547,000 ha. The present and past practice of clean tillage has undoubtedly contributed to problems of soil erosion, reduction in soil organic matter content, excessive drying of soil during crop senescence, loss of soil water reserves during fallow, and lack of adequate soil water at planting. The loss of soil water has resulted in greater irrigation requirements than would be needed if conservation agriculture practices were followed.

The water needs of major crops grown in Uzbekistan are not well known, contributing to overirrigation, high water tables, and increased salinization. Water for irrigation is stored in larger reservoirs upstream so that the water supply at the beginning

S. Evett, USDA-ARS, P.O. Drawer 10, Bushland, TX 79012; N. Ibragimov, Y. Esanbekov, and M. Sarimsakov, Uzbekistan Natl. Cotton Growing Res. Inst. (UNCGRI), P.O. Box Akkavak, Kibray District, Tashkent Province 702133, Uzbekistan; B. Kamilov, Uzbekistan Scientific Production Centre of Agric., Usman Usupov Str. 1, Tashkent City 700000, Uzbekistan; J. Shadmanov and R. Mirhashimov, Syrdarda Regional Exp. Stn., UNCGRI, P.O. Khamid Olimjon, Gulistan District, Syrdarya Province 708322, Uzbekistan; R. Musaev, Fergana Regional Experiment Station, UNCGRI, Kuva Town, Fergana Province 713910, Uzbekistan; T. Radjabov, Kashkadarya Regional Experiment Station, UNCGRI, Kasbi District, Kashkadarya Province 731204, Uzbekistan; B. Muhammadiev, Khorezm Regional Experiment Station, UNCGRI, Urgench District, Khorezm Province 740006, Uzbekistan. The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-ARS. Received 18 Oct. 2006. *Corresponding author (srevett@cprl.ars.usda.gov).

Vadose Zone J. 6:406–412
doi:10.2136/vzj2006.0155

of the irrigation season is fairly well known; the possibility of tailoring irrigation scheduling for alternative goals of larger water use efficiency or larger yield would exist if the relationships between irrigation scheduling regimes and yield and water use efficiency were known. Conservation tillage could conserve water by reducing evaporative losses and increasing rainfall infiltration. Unfortunately, preliminary efforts to apply conservation tillage to irrigated crops have resulted in reduced yields. Accurate soil water determinations are needed to discover the reasons for conservation tillage failure in irrigated agriculture.

FIG. 1. Map of Uzbekistan showing the locations of the six research stations where the neutron moisture meter was calibrated.

We proposed to establish the scientific basis for efficient irrigation management and scheduling by measuring the water use (evapotranspiration, ET) and yield of cotton, maize, and winter wheat at six research stations on six different but important irrigated soils of Uzbekistan. Water use was established using the soil water balance approach on a weekly basis. Considering ET as crop water use, P as precipitation, I as irrigation, R as the sum of runoff and run-on, F as flux across the lower boundary of the soil profile (control volume), and ΔS as the change in soil water stored in the profile, we know that the soil water balance must sum to zero:

$$\mathrm{ET} + \Delta S + R - P - I - F = 0$$

where the sign conventions are that (i) ET is taken as positive when water is lost to the atmosphere through transpiration and evaporation, and (ii) ΔS is positive when soil water storage increases during the season (Evett, 2002). Rearranging this equation gives the crop water use or ET as

$$\mathrm{ET} = -\Delta S + P + I - R + F$$

This approach required deep measurements of the soil profile water content, which was accomplished using NMMs. The NMM is a mature technology, well established in the literature, but requires calibration for each soil and soil layer (Hignett and Evett, 2002). Cultivated soils in Uzbekistan's arid and semiarid climates tend to have small organic matter contents (<3% w/w), but often do have horizons of carbonate accumulation, illuvial clay deposition, and in some cases texture stratification due to alluvial deposition. The objectives of this study were to establish that the NMM could be successfully calibrated to high accuracy in six soils of Uzbekistan representing the most important irrigated areas, to establish the importance of any soil horizon-specific calibrations, to investigate the chemical or physical reasons for any horizon-specific calibrations found, and to investigate the usefulness of the NMM through case studies of soil water dynamics under two crops.

Materials and Methods

The Uzbek National Cotton Growing Research Institute (UNCGRI) was established in 1929 and now encompasses 11 branch stations covering the important irrigated lands of the nation. Since independence in 1991, the UNCGRI has been given responsibility for crops in the cotton rotation such as maize, vegetables, and winter wheat, and the Institute has been designated to lead in crop water use investigations. Field experiments were conducted in different soil and climatic regions of Uzbekistan that comprise a major part of the irrigated zone, stretching from piedmont to semi-deserts (Fig. 1), including the Central Experiment Station of the UNCGRI near Tashkent, the Syrdarya Branch Station, and branch stations near Fergana, Kashkadarya, Khorezm, and Samarkand (Table 1).

The Russian soil classification is still in use in Uzbekistan (Umarov, 1975). In accordance with the UN classification, the soil at Tashkent is a Calcic Xerosol, the soils at Fergana and Samarkand are Calcaric Gleysols, the soils at the Khorezm and Syrdarya branch stations are Eutric Fluvisols, and the soil at Kashkadarya is a Takyric Yermosol (FAO, 2003). Soil particle size analysis was conducted using the pipette method (Day, 1965).

TABLE 1. Experiment stations at which neutron moisture meters were calibrated, including latitude and longitude, elevation above mean sea level, depth to water table, and type of soil formation according to the Russian system.

Station name	Location	Elevation	Depth to water table	Type of soil formation
		m	m	
Central (Tashkent)	41°42′ N, 69°49′ E	623	>15	automorphic
Fergana	40°23′ N, 71°46′ E	577	2–2.5	semi-hydromorphic
Kashkadarya	38°50′ N, 64°80′ E	180	>3	transitional from automorphic to hydromorphic
Khorezm	41°40′ N, 61°15′ E	120	1.5–2	hydromorphic
Samarkand	39°76′ N, 66°91′ E	706	>5	semi-hydromorphic
Syrdarya	40°50′ N, 68°80′ E	270	2–2.5	semi-hydromorphic

Calibration of the NMM (Campbell Pacific Nuclear International, Martinez, CA, Model 503DR1.5) was performed using methods described in Evett and Steiner (1995) and Hignett and Evett (2002). At each branch station, four polyvinyl chloride (PVC) plastic access tubes were installed in the field to 2.0-m depth. The field location was chosen to be representative of the soil at the branch station. To provide as wide a range of water contents as possible, calibrations were done when the field was as dry as possible, usually after a crop had depleted the soil water. A wet site was then created by placing a 0.3-m-high soil berm around a 15-m^2 area within which water was ponded until the wetting front had passed below the bottom of the access tubes. Two access tubes were in the wet site, and two in a nearby site in the dry field called the dry site. At each site, access tubes were placed 1.5 m apart. Access tubes in the wet site were 1.5 m from the inside edges of the berms. To avoid differences in water content between the time that NMM readings were taken and the time that soil was directly sampled for water content, the wet site was allowed to drain to field capacity before readings and sampling were done. Also, the two access tubes in the wet site were sampled one at a time. First, NMM readings were taken in one access tube and four soil samples were taken around that access tube at each depth of reading as quickly as possible afterward. Then, the soil pit thus created was filled, and NMM readings were taken in the second access tube, again followed quickly by soil sampling.

The PVC access tubes had a 50-mm inside diameter with a 2-mm wall thickness. Smaller diameter tubes that would more closely fit the 38-mm-diameter neutron probes were not available in the country; since a multilocation, multiyear research effort was planned, it was decided to use the locally available tubing. Before taking counts in the access tubes, five standard counts were taken with the NMM, mounted at >82 cm above the soil surface on a depth control stand (Evett et al., 2003) to remove any influence of soil wetness, and with the probe locked in its shield (Fig. 2, left). Counts in access tubes, including for the 10-cm depth, were also done using a depth control stand and were 60 s long. Count ratios were calculated by dividing each tube count by the mean of the standard counts.

Volumetric water content of soil profiles was measured by volumetric and gravimetric methods for regression relationships between NMM count ratio and water content. Two types of volumetric soil samplers were used. One was the 60-cm^3 Madera probe (Precision Machine Co., Lincoln, NE), which is a thin-walled tube probe that removes a core that is then cut to size using knives inserted through slots in the probe body (Hignett and Evett, 2002). The other sampler was a 100-cm^3 cylinder (Eijkelkamp Agrisearch Equipment, Giesbeek, the Netherlands, Part no. 07.01.53.NN), with a beveled lower edge, that was driven into the soil with a holder. The holder consisted of a rod-shaped handle attached to a cup that held the top of the cylinder during insertion, which was accomplished by hammering on the upper end of the handle rod (Part no. 07.05.01.53). Both devices enabled the user to avoid tilting of the sampler during insertion. This is important to avoid sample shattering and loosening. Also, both samplers allowed the user to quickly visually

FIG. 2. (Left) A neutron moisture meter in position on a depth control stand while recording a standard count. (Right) During calibration, four volumetric soil samples were taken around each access tube at each depth. Shown are the 100-cm^3 sampling cylinders.

compare the soil surface inside and outside the sampler body in situ to ascertain if compaction or loosening had occurred during insertion (Fig. 2, right). These sampler properties assured that samples represented the true bulk density and volumetric water content of the soils.

The NMM was read at depth increments of 20 cm, beginning at the 10-cm depth and descending. Four soil samples were taken close to each access tube and centered vertically at each depth of reading (Fig. 2, right). The four samples at each depth allowed the mean water content of the volume measured by the NMM to be well represented. Samples were sealed in cans and weighed to 0.01 g either in the field using a portable scale or in the laboratory as soon as possible. After drying at 105°C for 24 h, samples were weighed again. The mass difference, representing the water lost to drying, was converted to volume by dividing by the density of water. Volumetric water content of each sample was then computed as the volume of water lost to drying divided by the sample volume. Mean water content for each depth at each tube was calculated, omitting obvious outliers in bulk density or water content value. Outliers were identified by plotting bulk density and water content vs. depth and by comparing bulk density to water content. Large values of bulk density and water content for the same sample indicate compression of the soil sample. Small values of bulk density and water content for the same sample from dry soil often indicate sample shattering accompanied by dilation.

Calibration equations were calculated for the soils and important soil layers by linear regression of count ratios vs. volumetric water contents. Separate regressions were done for the 10-cm depth because of its nearness to the surface and the known influence of this proximity on the calibration equation (Evett et al., 2003; Hignett and Evett, 2002). Separate regressions were also calculated for soil horizons that were discovered during soil sampling or that were suggested by examination of data on soil particle size analysis and soil chemistry from the archives of the UNCGRI (e.g., Shamsiev, 2003; Slesareva and Rizhov, 1984). If regressions for separate horizons were not significantly different (slope comparison at the 0.10 level), the data for those horizons were combined and a single calibration reported for the combined horizons.

Finally, two example case studies were derived from data collected from studies of winter wheat water use at the Syrdarya Branch Station and the Central Experiment Station near Tashkent. Winter wheat was grown during the 2000–2001 season using four irrigation scheduling treatments based on percentages of the field capacity, F_C, which was 0.30 m^3 m^{-3} as determined from pressure plate work on undisturbed cores (Shamsiev, 2003):

Treatment 1. 65–65–60% of F_C
Treatment 2. 70–70–60% of F_C
Treatment 3. 75–75–60% of F_C
Treatment 4. 80–80–70% of F_C

TABLE 2. Calibration equations for neutron moisture meters (NMM) for different locations and soil layers in Uzbekistan. Equations are in terms of volumetric water content (θ, m^3 m^{-3}) and count ratio (CR). Soil layer depth limits indicate the first and last depth at which the particular calibration is appropriate.

Location	Soil layer	Equation	Water content range	r^2	RMSE
	cm		m^3 m^{-3}		m^3 m^{-3}
Central (Tashkent)	10	$\theta = 0.013 + 1.1752C_R$	0.10–0.32	0.989	0.011
H390104791†	30–70	$\theta = -0.176 + 0.3759C_R$	0.15–0.31	0.958	0.014
	90–160	$\theta = -0.039 + 0.2463C_R$	0.21–0.30	0.911	0.010
Fergana	10	$\theta = 0.077 + 0.2030C_R$	0.16–0.35	0.990	0.010
H390104792	30–90	$\theta = -0.262 + 0.4257C_R$	0.20–0.39	0.934	0.014
	110–150	Insufficient data range	0.32–0.35		
Kashkadarya	10	$\theta = 0.009 + 0.4029C_R$	0.03–0.32	0.983	0.021
H301105944	30–70	$\theta = -0.085 + 0.3143C_R$	0.04–0.37	0.986	0.017
	90–150	$\theta = -0.092 + 0.3254C_R$	0.04–0.39	0.973	0.024
	30–150	$\theta = -0.090 + 0.3211C_R$	0.04–0.39	0.979	0.021
Khorezm	10	$\theta = 0.020 + 0.263C_R$	0.13–0.37	0.974	0.021
H300205496	30–70	$\theta = -0.120 + 0.3467C_R$	0.18–0.36	0.929	0.018
	110–170	$\theta = -0.148 + 0.3404C_R$	0.11–0.41	0.970	0.016
Samarkand	0–10	$\theta = -0.101 + 0.4000C_R$	0.01–0.29	0.97	0.025
H360803351	30–160	$\theta = -0.063 + 0.2394C_R$	0.08–0.25	0.88	0.019
Syrdarya	10	$\theta = -0.021 + 0.3395C_R$	0.16–0.41	0.965	0.025
H300205497	30–50	$\theta = 0.051 + 0.2174C_R$	0.27–0.34	0.918	0.009
	70–170	$\theta = -0.010 + 0.2680C_R$	0.25–0.38	0.910	0.011

† Neutron moisture meter (NMM) serial number.

where each number in the sequence of three represents the percentage of field capacity that triggered an irrigation during each of the three main growth stages when profile water content fell to below that percentage. For example in Treatment 1, the first level of the 65–65–60% regime (65%) was used from germination to the tillering stage of the crop; the second level (65%) was used from tillering to the milk-wax stage of grain ripeness; and the third level (60%) was used from the milk-wax stage to full grain ripeness. Plots were triply replicated with one access tube per plot.

Results and Discussion

Reasonably precise calibration equations were obtained for all soils and soil horizons (Table 2). The root mean square error (RMSE) of regression ranged from 0.009 to 0.025 m^3 m^{-3}, with 11 of 17 values being <0.02 m^3 m^{-3}. We probably lost some accuracy because the access tubes were slightly larger than optimal, permitting more uncertainty in probe centering. Also, values of RMSE would probably be <0.01 m^3 m^{-3} for all calibrations if more samples were available; that is, if three, rather than two, access tubes had been used in each of the wet and dry sites (Evett, 2000; Evett and Steiner, 1995). Also, because many of the data reported here were gathered during training programs on NMM calibration and use, there may have been some loss of precision due to unfamiliarity with the NMM and soil sampling tools and methods.

Carbonate and Textural Effects on Calibrations

Distinctly different soil horizons and corresponding calibration equations were identified for four soils (Table 2), despite the uniformity of texture with depth for three of these soils (Tables 3–8). Due to nearness to the surface, equations for the 10-cm depth were always much different in slope from equations for deeper layers. Some soils exhibited either a textural or soil chemical change at deeper depths that resulted in different calibration equations for different depth ranges. Soils at Tashkent, Syrdarya, Kashkadarya, and Fergana were all fairly uniform in texture, ranging from silt to silty clay loam throughout the profile, and were probably derived from loess, either in place or in alluvial deposits (Tables 3–6). The soil at Khorezm is riverine in nature, consisting of a 70-cm-thick surface layer of silt loam underlain by fine sand, which is itself interspersed with lenses of clayey and silty materials.

At the Syrdarya Branch Station, larger contents of $CaCO_3$ and $CaSO_4$ at depths >70 cm caused distinctly different calibration equation slopes for the 30- to 50- and the 70- to 170-cm depth ranges (Table 2, Fig. 3). At the Tashkent Central Station, nodules and veins of $CaCO_3$ were noted during sampling at depths of >70 cm. Since the soil is a uniform silt loam, the different calibration curve for depths >70 cm is probably due to the increase in $CaCO_3$ concentration. Similar effects of Ca minerals on NMM calibration slopes have also been noted in the semiarid Great Plains of the USA, where slopes were likewise lower for soil layers rich in $CaCO_3$ (Evett and Steiner, 1995; Evett, 2000). Also, Van Bavel et al. (1956) found that in arid or semiarid zones, many soils have layers rich in $CaCO_3$ and $CaSO_4$ that require separate calibration. The effect is probably due to the presence of O in these minerals, which is relatively effective at causing thermalization of fast neutrons. The lowered calibration slope values would be expected in this case because the presence of O would increase the concentration of thermal neutrons and thus increase neutron counts without the presence of water.

TABLE 3. Textural composition of the moderately saline Calcaric Gleysol (meadow-sierozem soil) at the Fergana Branch Station of the Uzbekistan National Cotton Growing Research Institute.

Soil layer	Soil size fractions, mm							Texture
	1–0.25	0.25–0.1	0.1–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	
cm	g kg^{-1}							
0–32	12	29	25	290	125	243	276	silty clay loam
32–47	5	17	82	207	128	272	289	silty clay loam
47–60	5	13	09	192	310	140	331	silty clay loam
60–77	23	61	56	305	124	229	202	silt loam
80–90	52	101	54	346	119	152	176	silt loam
120–130	4	12	22	211	98	299	354	silty clay loam

TABLE 4. Textural composition of the slightly saline Takyric Yermosol (takyr soil) at the Kashkadarya Branch Station of the Uzbekistan National Cotton Growing Research Institute.

Soil layer	Soil size fractions, mm							Texture
	1–0.25	0.25–0.1	0.1–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	
cm	g kg^{-1}							
0–30	12	22	332	314	70	96	154	loam
30–70	5	10	186	307	58	170	264	silt loam
70–100	8	4	61	371	83	170	303	silty clay loam
100–150	4	8	246	474	98	50	120	silt loam
150–200	14	8	124	180	167	199	308	silty clay loam
200–250	36	25	189	160	96	199	295	silty clay loam

TABLE 5. Textural composition of the moderately saline Eutric Fluvisol (meadow-sierozem soil) at the Syrdarya Branch Station of the Uzbekistan National Cotton Growing Research Institute.

Soil layer	Soil size fractions, mm							Texture
	1–0.25	0.25–0.1	0.1–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	
cm	g kg^{-1}							
0–30	19	13	134	487	151	167	29	silt
30–40	21	13	121	481	158	161	45	silt
40–60	64	35	243	395	78	142	43	silt loam
60–80	61	56	307	398	62	81	35	silt loam
80–100	48	38	195	502	106	91	20	silt loam
100–120	86	19	120	509	87	105	74	silt loam
120–170	52	16	114	550	91	129	48	silt loam

TABLE 6. Textural composition of the Calcic Xerosol (old irrigated typical sierozem soil) at the Tashkent Headquarters of the Uzbekistan National Cotton Growing Research Institute (Shamsiev, 2003).

Soil layer	Soil size fractions, mm							Texture
	1–0.25	0.25–0.1	0.1–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	
cm	g kg^{-1}							
0–30	10	11	130	395	138	168	148	silt loam
30–50	13	12	160	402	128	151	134	silt loam
50–70	11	13	184	310	137	175	170	silt loam
70–100	10	10	132	352	140	182	174	silt loam
100–140	10	14	131	360	131	180	174	silt loam
140–170	16	21	204	371	107	146	135	silt loam
170–200	11	13	160	345	144	165	162	silt loam

TABLE 7. Textural composition of the Calcaric Gleysol (meadow-sierozem soil) at the Samarkand Branch of the Uzbekistan National Cotton Growing Research Institute.

Soil layer	Soil size fractions, mm							Texture
	1–0.25	0.25–0.1	0.1–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	
cm	g kg^{-1}							
0–30	13	39	153	279	154	227	135	silt loam
30–50	5	37	156	299	137	235	131	silt loam

TABLE 8. Textural composition of the slightly saline Eutric Fluvisol (irrigated meadow alluvial soil) at the Khorezm Branch Station of the Uzbekistan National Cotton Growing Research Institute.

Soil layer	Soil size fractions, mm							Texture
	1–0.25	0.25–0.1	0.1–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	
cm	g kg^{-1}							
0–24	39	59	167	389	102	137	107	silt loam
24–40	31	64	175	332	122	145	131	silt loam

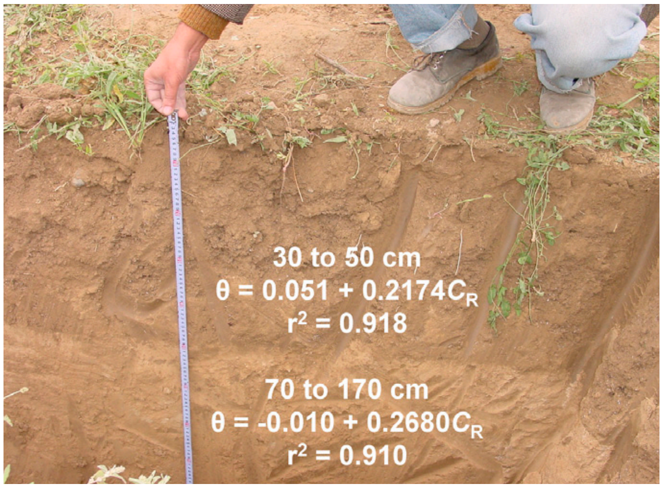

FIG. 3. Soil profile at Syrdarya Branch Station, Uzbekistan National Cotton Growing Research Institute, showing the layer below 70-cm depth that is enriched with $CaCO_3$ and $CaSO_4$, which causes a difference in the neutron moisture meter calibration equations. Equations are shown in terms of volumetric water content (θ, $m^3 m^{-3}$) and count ratio (C_R).

Data for the 110- to 150-cm depth layer at Fergana Branch Station did not cover a sufficient range of water contents to provide a useful calibration in that depth range. Crop and irrigation management will be used to dry the deeper soil profile for a subsequent calibration exercise. Calibrations for the Kashkadarya Branch Station were calculated separately for the 30- to 70-cm depth range and the 90- to 150-cm depth range due to the slightly increased clay content of the deeper layers (Table 4). However, there was little difference between equation slopes and intercepts for the two layers, and a single equation for the 30- to 150-cm depth range was just as effective for prediction of water content (Table 2). At Khorezm, calibration equations for the 30- to 70- and 110- through 170-cm layers were quite similar even though soil textures were different (silt loam and fine sand, textured by hand). Unfortunately, laboratory particle size data were not available for depths >25 cm (Table 8). Data from the 90-cm depth near the interface between these layers were omitted due to the high noise present in those values. Attempting a single calibration equation for depths ≥30 cm (excluding data for 90 cm), however, caused the RMSE value to increase by 0.01 $m^3 m^{-3}$ and the r^2 value to decrease to 0.91; therefore, separate calibration equations were retained for these layers.

TABLE 9. Change in water content, change in profile water storage, irrigation, evapotranspiration (ET), yield), and water use efficiencies at Tashkent for the 2000–2001 winter wheat season. Precipitation during the season was 249 mm.

Depth	Irrigation scheduling treatment (% of field capacity)			
	65–65–70	70–70–60	75–75–60	80–80–70
cm	Volumetric water content, $m^3 m^{-3}$			
20	0.006	0.031	0.017	0.036
40	−0.020	−0.022	−0.020	−0.026
60	−0.022	−0.027	−0.037	−0.034
80	−0.044	−0.057	−0.073	−0.073
100	−0.028	−0.056	−0.070	−0.077
120	−0.028	−0.045	−0.077	−0.088
140	−0.021	−0.048	−0.062	−0.080
	Change in storage, mm			
	−41.7	−49.5	−56.9	−56.3
	Irrigation, mm			
	86	84	167	255
	ET, mm			
	293	284	359	448
	Grain yield, Mg ha^{-1}			
	4.01	4.58	4.99	5.01
	Irrigation water use efficiency, kg m^{-3}			
	4.66	5.45	2.99	1.96
	Water use efficiency, kg m^{-3}			
	1.37	1.62	1.39	1.12

† Each number in the sequence of three represents the percentage of field capacity that triggered an irrigation during each of the three main growth stages when profile water content fell to below that percentage.

Case Studies

Data presented for the Tashkent research center are for the spring irrigation season. Because precipitation during this time was not large, runoff and run-on were negligible. Soil water content at the bottom of the profile was small enough throughout the season (data not shown) that water flux at the bottom of the control volume could be considered to be negligible.

The value of ET for the largest irrigation rate (Treatment 4) was 448 mm (Table 9). This compared well with values ranging from 424 to 524 mm for fully irrigated winter wheat grown at Bushland, TX (Evett et al., 1995), which has a similar continental, semiarid climate. Treatments 1 through 3 were deficit irrigation treatments, resulting in ET ranging from 293 to 359 mm, respectively (Table 9). The total water use efficiency (WUE) values also compared well with WUE values ranging from 0.6 to 1.2 kg m^{-3} reported by Musick et al. (1994) for irrigated winter wheat at Bushland. Not surprisingly, the deficit irrigation treatments resulted in larger water use efficiency, but with smaller yields. The 75–75–60% treatment (Treatment 3) resulted in a WUE increase from 1.12 to 1.39 kg m^{-3} compared with the most well irrigated treatment (Treatment 4), but with only a slight decrease in yield, 0.02 Mg ha^{-1}, respective to Treatment 4. Even larger increases in WUE and irrigation water use efficiency resulted from Treatment 2, but with a more important decrease in yield. Irrigation water use efficiency was largest for Treatment 2 and more than double that for Treatment 4, with only a 9% decline in yield. Thus, either the irrigation scheduling regime of Treatment 2 (70–70–60% of F_C) or Treatment 3 (75–75–60% of F_C), could be used, with the 70–70–60% of F_C regime being preferable in water-short years and the 75–75–60% of F_C regime being preferable in years with plentiful water.

The second example is drawn from a study of winter wheat water use at the Syrdarya Branch Station during the 2000–2001 season (Fig. 4). Heavy winter precipitation after 15 Jan. 2001

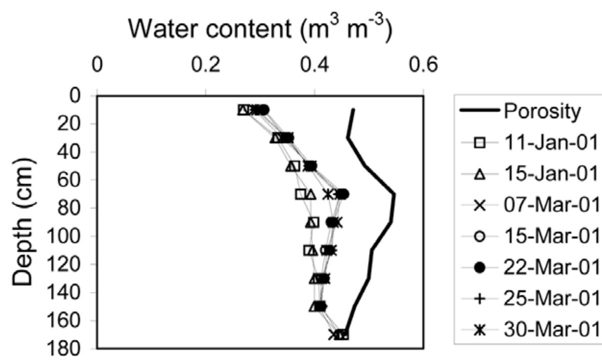

FIG. 4. Evolution of profile volumetric water content at the Syrdarya Branch Station in one treatment, showing that a water table existed at the 170-cm depth.

caused water contents to increase in the upper profile, while at the 170-cm depth water contents remained practically constant because the soil was saturated at that depth. Because volumetric soil samples were taken during NMM calibration, the profile porosity was easily calculated from the soil bulk density values obtained; and plotting the porosity with the water content values confirmed the presence of a water table at 170 cm. This suggests that considerable vertical soil water flux could have occurred into or out of the control volume used to calculate crop water use by the soil water balance method. These data suggest that the soil water balance method based on an unclosed control volume will not succeed at the Syrdarya Station. A weighing lysimeter with a controlled water table would be an approach more likely to succeed.

Conclusions

Overall, the precision of calibration equations was acceptable for research objectives involving measurement of crop water use. We conclude that the NMM can be usefully calibrated and successfully used for crop water use and water use efficiency studies in the major irrigated soils of Uzbekistan except where high water tables exist. We also conclude that irrigation scheduling regimes corresponding to percentages of field capacity during the three major growth phases of winter wheat can be successfully used to improve water use efficiency of winter wheat in Uzbekistan. This knowledge can be used to tailor irrigation applications, depending on the condition of irrigation water supplies at the beginning of the season so that either larger water use efficiency or larger yield can be chosen as the irrigation goal.

When we began these studies, we were also involved in comparisons of the laboratory and field performance, including accuracy of profile water content determinations, of several alternative sensors that were deployed in plastic access tubes for soil profile water content determinations. These sensors were all based on electromagnetic (EM) properties of the soil as influenced by soil water content. Our hope was that one of the EM devices would prove sufficiently accurate for use in irrigation scheduling, thus avoiding the difficulties that we saw in routine use of the NMM, which is highly regulated. Unfortunately, none of the EM devices proved sufficiently accurate for either irrigation management or scientific work. We do feel that the NMM continues to be useful for scientific work, including work that determines water use efficiency as influenced by irrigation method and management. Ibragimov et al. (2007) is an example of such use for determining cotton water use efficiency in Uzbekistan under drip and furrow irrigation at three irrigation rates. Results from these studies are useful for farmer decisions about irrigation system purchases and for policy decisions.

Acknowledgments

We gratefully acknowledge support under Grant no. ZB1-2050, “Improving Water Use Efficiency/Reducing Salinization in Irrigated Wheat and Sugar Beet Production”, from the U.S. Civilian Research and Development Foundation; and under Technical Co-operation Project no. UZB/5/002, “Optimization of Water and Fertilizer Use for Major Crops”, and IAEA Research Contract no. 11186/FAO, “Accuracy and Precision of Neutron Scattering, TDR, and Capacitance Methods of Soil Water Measurement”, both from the Joint Division of the International Atomic Energy Agency and FAO, Vienna, Austria.

References

Day, P.R. 1965. Particle fractionation and particle-size analysis. p. 545–567. *In* C.A. Black (ed.) Methods of soil analysis. Part 1. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Evett, S.R. 2000. Some aspects of time domain reflectometry (TDR), neutron scattering, and capacitance methods of soil water content measurement. p. 5–49. *In* Comparison of soil water measurement using the neutron scattering, time domain reflectometry and capacitance methods. Int. Atomic Energy Agency, Vienna.

Evett, S.R. 2002. Water and energy balances at soil–plant–atmosphere interfaces. p. 127–188. *In* A.A. Warrick (ed.) The soil physics companion. CRC Press, Boca Raton, FL.

Evett, S.R., T.A. Howell, A.D. Schneider, and J.A. Tolk. 1995. Crop coefficient based evapotranspiration estimates compared with mechanistic model results. Water Resour. Eng. 2:1585–1589.

Evett, S.R., and J.L. Steiner. 1995. Precision of neutron scattering and capacitance type moisture gages based on field calibration. Soil Sci. Soc. Am. J. 59:961–968.

Evett, S.R., J.A. Tolk, and T.A. Howell. 2003. A depth control stand for improved accuracy with the neutron probe. Vadose Zone J. 2:642–649.

FAO. 2003. Fertilizer use by crop in Uzbekistan. Available at www.fao.org/docrep/006/y4711e/y4711e00.htm (verified 20 Feb. 2007). FAO, Rome.

Hignett, C., and S.R. Evett. 2002. Neutron thermalization. p. 501–521. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Ibragimov, N., S.R. Evett, Y. Esanbekov, B.S. Kamilov, L. Mirzaev, and J.P.A. Lamers. 2007. Water use efficiency of irrigated cotton in Uzbekistan under drip and furrow irrigation. Agric. Water Manage. (in press), doi:10.1019/j.agwat.2007.01.016.

Mirzajanov, K.M. 1981a. Scientific basis of the fight against wind erosion on irrigated soils of Uzbekistan. USSR Ministry of Agriculture, Tashkent, Uzbekistan.

Mirzajanov, K.M. 1981b. Soil erosion. p. 293–298. *In* Compendium on cotton growing. Central Asian Dep. of All-Union Academy of Agric. Sci., Tashkent, Uzbekistan.

Musick, J.T., O.R. Jones, B.A. Stewart, and D.A. Dusek. 1994. Water–yield relationships for irrigated and dryland wheat in the U.S. southern plains. Agron. J. 86:980–986.

Shamsiev, A.C. 2003. Water use and irrigation mode of new cotton varieties (C-6524, Akdarya 5, Andijon-33, Andijon-34) in irrigated typical sierozem soils of Tashkent Province. Ph.D. diss. Uzbekistan Cotton Growing Research Inst., Tashkent.

Slesareva, L.N., and S.N. Rizhov. 1984. Importance of soil structure and soil compaction for productivity of irrigated sierozem soils. Uzbekistan Academy of Sci., Tashkent.

Umarov, M.U. 1975. Soils of Uzbekistan. FAN, Tashkent, Uzbekistan.

Van Bavel, C.H.M., N. Underwood, and R.W. Swanson. 1956. Soil moisture measurement by neutron moderation. Soil Sci. 82:29–41.