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Soil moisture neutron probe calibration and use in five soils of Uzbekistan

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Abstract

Efforts to place irrigation scheduling in Uzbekistan on a scientific footing begin with measurement of crop water use under its climate, soils, and other environmental factors. Crop water use may be calculated from the soil water balance if changes in soil water storage due to irrigation and precipitation and crop water uptake can be accurately measured, and if losses to deep percolation or upward fluxes from shallow water tables can be eliminated in the experimental setup. We detail accurate field calibrations of soil moisture neutron probes (SMNP) at five locations in Uzbekistan, in soils ranging from deep, uniform silt loams of loessal origin to highly stratified alluvial soils near the Amu Darya river. All calibrations involved creating a wet site containing at least two access tubes in a field that was otherwise as dry as possible. Two access tubes were also installed in the dry field so that a wide range of water contents could be sampled at each depth in the soil. This allowed us to discern whether different calibrations pertained to different soil layers or horizons. 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 $CaCO_3$ and/or $CaSO_4$ content of 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 near 70-cm depth caused separate calibration equations for the 30 to 70-cm depth range (silt loam) and the 110 to 170-cm depth range (fine sand). Calibration at the Fergana Branch Station was successful for the 10-cm and the 30 to 90-cm depth ranges. Root mean squared errors (RMSE) of calibration were in the range of 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, one for winter wheat and one for cotton, both in 2001. Soil water contents measured in winter wheat at the Syrdarya Branch Station showed the presence of a water table that hindered calculation of crop water use. Similar measurements under cotton at Tashkent showed that the soil profile remained well below saturation throughout the irrigation season, minimizing deep percolation losses, and allowing cotton water use to be successfully calculated by soil water balance.

Keywords: neutron scattering, soil water storage, profile water content, calibration, access tube, water table

Introduction

Irrigation in the Republic of Uzbekistan is important to the economy and ecology of the region. Presently, 60 to 65% of gross national income is from agriculture and cotton production makes up about 50% of the gross national product. The nation of 24 million people encompasses 447,000 square kilometers, about half of which is desert. Uzbekistan irrigates about 4 million ha of land, much of which is in the wide flood plains of the Syr Darya and Amu Darya rivers, which are subject to periodic high water tables and soil salinization. Cotton and wheat are major crops in the country, followed by corn, alfalfa, sugar beet, vegetables and fruits. Due to its deep continental geographic location, the country's precipitation is low and erratic. Thus, agricultural production in the country, as well as in the whole 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 the ecological crisis zone around the sea. The water needs of major crops grown in Uzbekistan are not well known, leading to over-irrigation, high water tables, and increased salinization.

We proposed to establish the scientific basis for efficient irrigation management and scheduling by measuring the water use of winter wheat, sugar beet, and cotton at five research stations on five differing but important soils of Uzbekistan. Water use was established using the soil water balance approach on a weekly basis. This approach required deep measurements of the soil profile water content, which was accomplished using soil moisture neutron probes (SMNP). The SMNP is a mature technology, well established in the literature, but requires calibration for each soil and soil layer (Hignett and Evett, 2002). The objectives of this study were to establish that the SMNP could be successfully calibrated to high precision in five soils of Uzbekistan, to establish the importance of any soil horizon-specific calibrations and to investigate the chemical or physical reasons for any horizon-specific calibrations found, and to investigate the usefulness of the SMNP 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 eleven branch stations covering the important irrigated lands of the nation. Since Independence in 1991, the role of the UNCGRI has grown to encompass responsibility for crops such as winter wheat and sugar beet, 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, including the:

Central Experiment Station of UNCGRI in Tashkent: old irrigated typical gray soil, medium loam; water table is >15 m deep (automorphic type of soil formation);

Syrdarya Branch Station: meadow-gray soil, light loam, moderate saline; water table level is 2.0 to 2.5-m deep (semi-hydromorphic type of soil formation);

Fergana Branch Station: meadow-saz soil, silt loam;

Khorezm Branch Station: old irrigated meadow alluvial soil, clay loam, light saline; water table is 1.5 to 2.0-m deep (hydromorphic type of soil formation);

Kashkadarya Branch Station: newly irrigated "takyr" soil, clay loam, light saline; water table is >3.0-m deep (transitional soils from the automorphic to hydromorphic).

Calibration of the SMNP (Campbell Pacific Nuclear International, Inc.[1], Martinez, CA, USA, model 503DR1.5) was performed using methods described in Evett and Steiner (1995). At each location, polyvinyl chloride (PVC) plastic access tubes were installed in the field to 2.0-m depth, in two replicates in each of two plots of 10 square meters each. A wet site plot was irrigated to field capacity by berming the area and ponding water until the wetting front descended below the bottoms of the access tubes, then waiting until the soil drained to field capacity. Preparation of a non-irrigated plot to be the dry site was done by crop and field management over the preceding season. 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. Prior to taking counts in the access tubes, five standard counts were taken with the SMNP mounted at >82 cm above the soil surface on a depth control stand[2] or tall access tube to remove any influence of soil wetness, and with the probe locked in its shield (Figure 1, Left). Counts in access tubes 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/gravimetric methods for use in establishing regression relationships between SMNP count ratio and water content.

Two types of volumetric soil samplers were used. One was the 60 cm^3 Madera probe (Precision Machine Company, Lincoln, NE, USA), 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. The other 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 compare the soil surface inside and outside the sampler body in situ to ascertain if compaction or loosening had occurred during insertion. These sampler properties

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[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

[2] Evett, S.R. 2000. Construction of a Depth Control Stand for Use with the Neutron Probe [Online]. 7 pp. USDA-ARS-SPA-CPRL, Bushland, TX. Available at http://www.cprl.ars.usda.gov/programs/.

assured that samples represented the true bulk density and volumetric water content of the soils.

Figure 1 Left: A soil moisture neutron probe in position on a depth control stand while recording a standard count. Right: Four volumetric soil samples were taken around each access tube at each depth. Shown are the 100 cm^3 sampling cylinders.

Four soil samples were taken close to each access tube at each depth of reading for the SMNP (Figure 1, Right). The SMNP was read at depth increments of 20 cm, beginning at 10-cm depth and descending. The four samples allowed the mean water content of the volume measured by the SMNP 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.

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 nearness on the calibration equation (Hignett and Evett, 2002). Separate regressions were also done 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. If regressions for separate horizons were not significantly different, the data for those horizons were combined and a single calibration reported for the combined horizons. Two example case studies were derived from data collected from studies of wheat and cotton water use at Syrdarya Branch Station and Tashkent, respectively, in 2001.

Results and Discussion

Reasonably precise calibration equations were obtained for all soils and soil horizons. The root mean squared error of regression ranged from 0.009 to 0.025 $m^3\ m^{-3}$, with 10 of 14 values being less than 0.02 $m^3\ m^{-3}$ (Table 1). Distinctly different soil horizons were identified for all five soils. 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 caused there to be 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 are probably derived from loess, either in place or in alluvial deposits (Tables 2-5). The soil at Khorezm is alluvial in nature, consisting of a 70-cm thick surface layer of silty clay loam underlain by fine sand, which is itself interspersed with lenses of clayey and silty materials (data not available).

Table 1 Calibration equations for soil moisture neutron probes (SMNP) for different locations and soil layers in Uzbekistan. Equations are in terms of volumetric water content (θ, $m^3\ m^{-3}$) and count ratio (C_R).

Location	Soil layer (cm)	Equation	r^2	RMSE** ($m^3\ m^{-3}$)
Tashkent #H390104791*	10	$\theta = 0.013 + 1.1752C_R$	0.989	0.011
	30 – 80	$\theta = -0.176 + 0.3759C_R$	0.958	0.014
	80 – 160	$\theta = -0.039 + 0.2463C_R$	0.911	0.010
Syrdarya #H300205497	10	$\theta = -0.021 + 0.3395C_R$	0.965	0.025
	30 – 50	$\theta = 0.051 + 0.2174C_R$	0.918	0.009
	70 – 170	$\theta = -0.010 + 0.2680C_R$	0.910	0.011
Kashkadarya #H301105944	10	$\theta = 0.009 + 0.4029C_R$	0.983	0.021
	30 – 70	$\theta = -0.085 + 0.3143C_R$	0.986	0.017
	90 – 150	$\theta = -0.092 + 0.3254C_R$	0.973	0.024
	30 – 150	$\theta = -0.090 + 0.3211C_R$	0.979	0.021
Khorezm #H300205496	10	$\theta = 0.020 + 0.263C_R$	0.974	0.021
	30 – 70	$\theta = -0.120 + 0.3467C_R$	0.929	0.018
	110 – 170	$\theta = -0.148 + 0.3404C_R$	0.970	0.016
Fergana #H390104792	10	$\theta = 0.077 + 0.2030C_R$	0.990	0.010
	30 – 90	$\theta = -0.262 + 0.4257\ C_R$	0.934	0.014
	110 – 150	Insufficient data range		

*The # sign denotes the SMNP serial number.

**RMSE is root mean squared error of regression.

Table 2 Mechanical composition of the meadow-saz soil type at the Fergana Branch Station of the UNCGRI.

Soil layer (cm)	Percentage (%) of soil fractions (sizes) (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	
0-32	1.2	2.9	2.5	29.0	12.5	24.3	27.6	Silty clay loam
32-47	0.5	1.7	8.2	20.7	12.8	27.2	28.9	Silty clay loam
47-60	0.5	1.3	0.9	19.2	31.0	14.0	33.1	Silty clay loam
60-77	2.3	6.1	5.6	30.5	12.4	22.9	20.2	Silt loam
80-90	5.2	10.1	5.4	34.6	11.9	15.3	17.6	Silt loam
120-130	0.4	1.2	2.2	21.1	9.8	29.9	35.4	Silty clay loam

Table 3 Mechanical composition of the takyr soil type at the Kashkadarya Branch Station of the UNCGRI.

Soil layer (cm)	Percentage (%) of soil fractions (sizes) (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	
0-30	1.2	2.2	33.2	31.4	7.0	9.6	15.4	Loam
30-70	0.5	1.0	18.6	30.7	5.8	17.0	26.4	Silt loam
70-100	0.8	0.4	6.1	37.1	8.3	17.0	30.3	Silty clay loam
100-150	0.4	0.8	24.4	47.2	9.6	4.8	11.8	Silt loam
150-200	1.4	0.8	12.4	18.0	16.7	19.9	30.8	Silty clay loam
200-250	3.6	2.5	18.9	16.0	9.6	19.9	29.5	Silty clay loam

Table 4 Mechanical composition of the grey-meadow soil type at the Syrdarya Branch Station of the UNCGRI.

Soil layer (cm)	Percentage (%) of soil fractions (sizes) (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	
0-30	1.9	1.3	13.4	48.7	15.1	16.7	2.9	Silt
30-40	2.1	1.3	12.1	48.1	15.8	16.1	4.5	Silt
40-60	6.4	3.5	24.3	39.5	7.8	14.2	4.3	Silt loam
60-80	6.1	5.6	30.5	39.8	6.2	8.1	3.5	Silt loam
80-100	4.8	3.8	19.5	50.2	10.6	9.1	2.0	Silt loam
100-120	8.6	1.9	12.0	50.9	8.7	10.5	7.4	Silt loam
120-170	5.2	1.6	11.4	55.0	9.1	12.9	4.8	Silt loam

Table 5 Mechanical composition of the old irrigated typical grey soil type at the Tashkent Headquarters of the UNCGRI.

Soil layer (cm)	Percentage (%) of soil fractions (sizes) (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	
0-30	1.3	1.1	12.5	37.4	13.6	16.9	17.7	Silt loam
30-50	1.5	1.2	15.4	39.4	14.1	13.9	14.5	Silt loam
50-70	1.1	0.9	17.9	31.7	14.2	16.6	17.4	Silt loam
70-100	1.0	1.1	14.2	36.8	13.7	18.6	14.7	Silt loam

At Syrdarya, larger contents of $CaCO_3$ and $CaSO_4$ at depths greater than 70 cm caused distinctly different calibration equation slopes for the 30 to 50-cm and the 70 to 170-cm depth ranges (Table 1, Figure 2). At Tashkent, 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 calcium minerals on SMNP calibration slopes have also been noted in the semiarid Great Plains of the United States, where slopes were likewise lower for soil layers rich in $CaCO_3$ (Evett and Steiner, 1995; Evett, 2000). The effect is probably due to the presence of oxygen 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 oxygen would increase the concentration of thermal neutrons and thus increase neutron counts without the presence of water. Data for the 110 to 150-cm depth layer at Fergana 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.

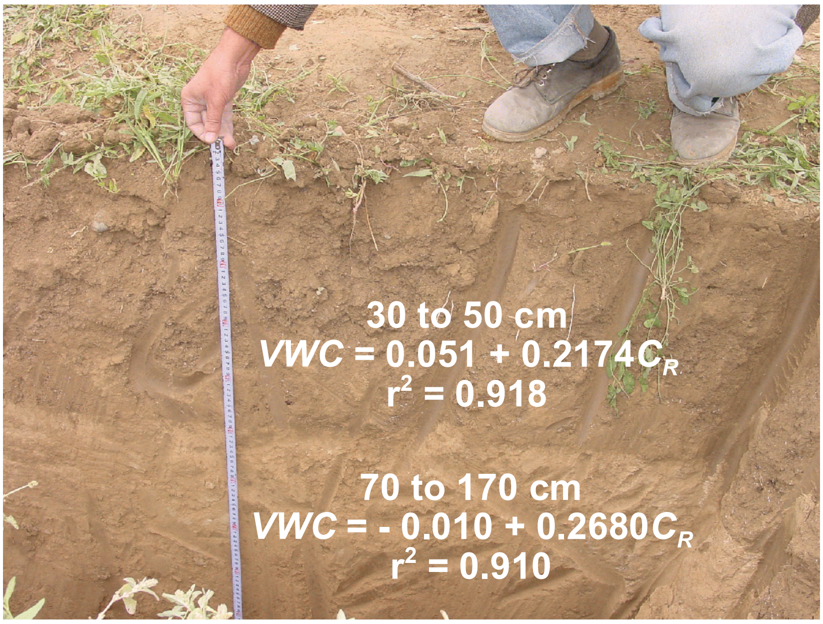

Figure 2 Soil profile at Syrdarya Branch Station, UNCGRI, Uzbekistan showing the layer below 70-cm depth that is enriched with $CaCO_3$ and $CaSO_4$, which causes a difference in the SMNP calibration equations. Equations are shown in terms of volumetric water content (VWC, $m^3\ m^{-3}$) and count ratio (C_R).

Calibrations for Kashkadarya 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 3). 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 1). At Khorezm, calibration equations for the 30 to 70-cm and 110 through 170-cm layers were quite similar even though soil textures were different. Data from the 90-cm depth near the interface between these layers were omitted due to the high noise present in those values. However, attempting a single calibration equation for depths ≥30 cm (excluding data for 90-cm) caused the RMSE value to increase by 0.01 $m^3\ m^{-3}$ and the r^2 value to decrease to 0.91; so, separate calibration equations were retained for these layers.

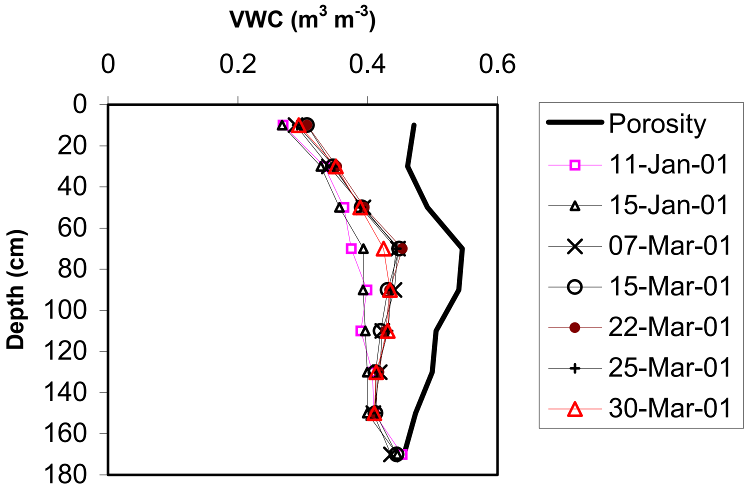

Figure 3 Evolution of profile volumetric water content (VWC) at the Syrdarya Branch Station in one treatment, showing that a water table existed at 170-cm depth. Means of values from three access tubes.

Two examples of data gathered with the SMNP for crop water use determination will conclude our discussion. At Syrdarya Branch Station, profile water content was measured under winter wheat during the 2000-2001 season (Figure 3). Heavy winter precipitation after 15 Jan. 2001 caused water contents to increase in the upper profile, while at 170-cm depth water contents remained practically constant because the soil was saturated at that depth. Because volumetric soil samples were taken during SMNP 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. The second example is drawn from a cotton water use study conducted at the UNCGRI Headquarters near Tashkent in 2001 (Figure 4). Water contents remained well below the maximum allowed by the soil porosity. Application of the soil water balance equation, using measured irrigation, rainfall and soil water content changes, allowed calculation of cotton water use for the season.

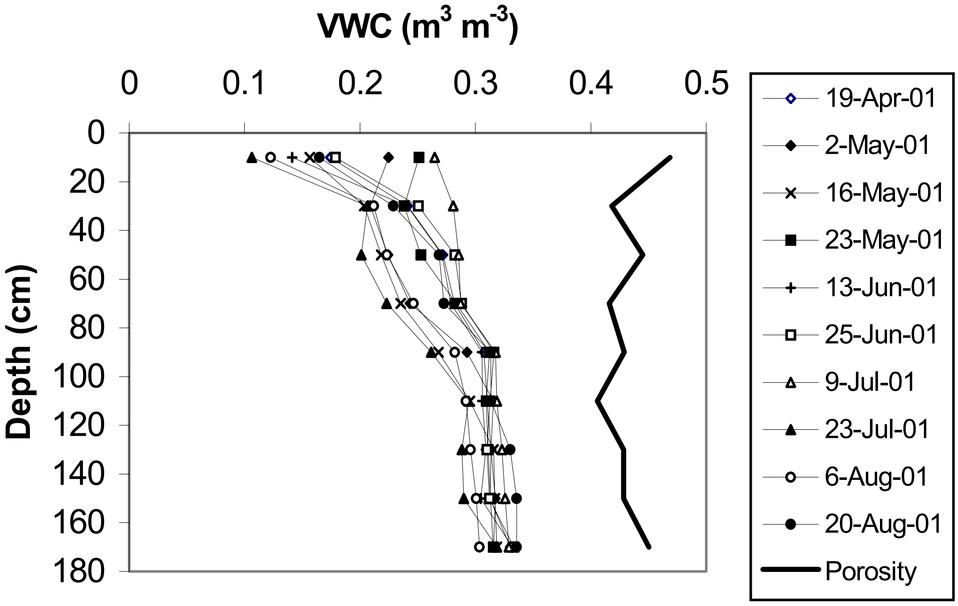

Figure 4 Evolution of profile volumetric water content (VWC) at the UNCGRI, Tashkent during the cotton irrigation season in 2001.

Conclusions

Overall, the precision of calibration equations was acceptable for research objectives involving measurement of crop water use. Values of RMSE would probably be less than 0.01 m^3 m^{-3} 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, respectively (Evett, 2000; Evett and Steiner, 1995). Also, because much of the data reported here was gathered during training programs on SMNP calibration and use, there may have been some loss of precision due to unfamiliarity with the SMNP and soil sampling tools and methods. We conclude that the SMNP can be usefully calibrated and successfully used in major irrigated soils of Uzbekistan except where high water tables exist.

Acknowledgements

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