Use of Neutron Probe for Investigations of Winter Wheat Irrigation Scheduling in Automorphic and Semi-Hydromorphic Soils of Uzbekistan

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Cotton and wheat are the major crops in Uzbekistan followed by corn, alfalfa, sugar beet, vegetables and fruits. Owing to its deep continental geographic location, the country has little and erratic precipitation. Thus, agricultural production in the country, like in the whole of Central Asia, is predominantly based on irrigation, which makes irrigation water supply the prevailing factor limiting crop yields in the region. It should be noted that winter wheat has been grown since ancient times on limited areas of the Uzbekistan piedmont; but its production in recent years has been far less than enough for the country. Therefore, a major part of bread wheat was imported from other parts of the former Soviet Union as well as from other countries. Since the country's independence in 1991, wheat production has grown so that today approximately one million ha of irrigated winter wheat and 200 000 ha of dry-land wheat are produced. Although the area under winter wheat has increased, yields are relatively low. Low yields are partly caused by incorrect irrigation scheduling that causes yield loss, which is due to stress in some cases and due to fertilizer lost with deep percolation in other cases. Therefore, investigation of crop water use and optimal irrigation scheduling for winter wheat in different climatic and soil conditions of the country is required.

Our investigations of water use (evapotranspiration or ET) and irrigation scheduling of winter wheat were conducted at two research stations on two differing soils of Uzbekistan, for the autumn-summer periods of 2000-2001 and 2001-2002. 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 main goal of the research was to develop optimal parameters for water use (ET) and irrigation scheduling for winter wheat and other major crops of Uzbekistan.

METHODS and MATERIALS

Field experiments were conducted in different soil and climatic regions of Uzbekistan that comprise a major part of the irrigated zone, including the:

- Central Experiment Station of Uzbekistan's Cotton Growing Research Institute in Tashkent: old irrigated typical gray soil, medium loam; water table is more than 15-m deep (automorphic type of soil formation).
- Syrdarya Branch Station of the Institute: meadow-gray soil, light loam, moderately saline; underground water level is 2.0 to 2.5-m deep (semi-hydromorphic type of soil formation)

An important key thrust of the investigations was the measurement of soil profile water content. For this purpose we used the soil moisture neutron probe (SMNP) (Campbell Pacific Nuclear International, model Hydroprobe-503DR1.5), which was calibrated for each soil condition.

Calibration of the SMNP was performed using methods described in Evett and Steiner (1995). The PVC 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 using approx. 4,500 m^3 of irrigation water. Preparation of a non-irrigated plot as the dry site was done by crop and field management over the preceding season. Volumetric water content of the soil profiles was measured by both SMNP and volumetric/gravimetric methods for comparison. Calibration equations were calculated for the soils and important soil layers. These were used for determination of irrigation rates and times for winter wheat during the growing season.

Measurements of volumetric water content of the soil profile were conducted twice a week and in two replicates during the experiments by SMNP to 2-m depth and for each 20-cm soil layer separately. Before each measurement, a standard count (C_S) of the SMNP was determined in five replicates. As a starting point for investigations of irrigation scheduling, we adopted the field capacity (F_C) index, which was for: Tashkent, 0.298 m^3 m^{-3}; and Syrdarya, 0.348 m^3 m^{-3}. Irrigations were scheduled when soil moisture in the root zone was depleted by the crop to specific fractions of F_C (for instance, irrigation at 70% of F_C).

Winter wheat water use was measured by the soil water balance method. Considering ET as crop water use, P as precipitation, I as Irrigation, R as the sum of runoff and runon, F as flux across the lower boundary of the soil profile (control volume), and ΔS as change in soil water stored in the profile, we know that the soil water balance must sum up to zero:

$$ET + \Delta S + R - P - I - F = 0 \qquad (1)$$

where the sign conventions are as given in Evett (2002), including the convention that ET is taken as positive when water is lost to the atmosphere through transpiration and/or evaporation. Re-arranging this equation gives the crop water use or ET as:

$$ET = -\Delta S + P + I - R + F \qquad (2)$$

The experiments with winter wheat were carried out in three replicates and comprised four treatments. Each treatment consisted of scheduling irrigations at specific percentages of F_C during each of three plant growth periods as follows:

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

where the first of the three levels of F_C (e.g. **65**-65-60%) was used from germination to shooting stage of the crop; the second level (e.g. 65-**65**-60%) was used from shooting to the milk-wax stage of grain ripeness; and the third level (e.g. 65-65-**60**%) was used from the milk-wax stage to full grain ripeness. Plot area in the experiments was 240 m^2 (4.8 m by 50 m). Irrigation water quantity used for each treatment was measured with a weir (Weir of Chippoletty). Fertilizer was applied at rates of 200 kg ha^{-1} N, 140 kg ha^{-1} P, and 100 kg ha^{-1} K.

RESULTS and DISCUSSION

SMNP Calibration

Reasonably precise calibration equations were obtained for both 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 both soils. Also, due to nearness to the surface, equations for the 10-cm depth were different in slope from equations for deeper layers. Soils at both Tashkent and Syrdarya were 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 2-3).

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

*The # sign denotes the SMNP serial number.

**RMSE is root mean squared error of regression.

Table 2. Mechanical composition of the grey-meadow soil type at Syrdarya Branch Station of Uzbekistan Cotton Growing Research Institute.

Soil layer (cm)	Percentage (%) of soil fractions (sizes) (mm)							
	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	Texture
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 3. Mechanical composition of the old irrigated typical grey soil type at the Tashkent Headquarters of the Uzbekistan Cotton Growing Research Institute.

Soil layer (cm)	Percentage (%) of soil fractions (sizes) (mm)							
	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	Texture
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, large amount 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). 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 semi-arid 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 in 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.

Two examples of data gathered with the SMNP for crop water use determination will be illustrated. At Syrdarya Branch Station, profile water content was measured under winter wheat during the 2000-2001 season. Heavy winter precipitation after 15 Jan. 2001 caused water contents to increase in the upper profile, while water content remained practically constant at 170-cm depth because the soil was saturated at that depth (Fig. 1). 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 winter wheat water use study conducted at the Cotton Research Institute Headquarters near Tashkent in 2001. Water content remained well below the maximum allowed by the soil porosity (Fig. 2). 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.

Crop water use

Because of shallow water tables at Syrdarya, flux (F) across the lower boundary could not be considered negligible, and it was not possible to calculate the ET of the crop for this location. It will be possible to measure ET if special weighing lysimeters are constructed at the Branch Stations of the Institute or elsewhere in Syrdarya.

The sum of runoff and runon (R) and the flux (F) were zero for automorphic soils of Tashkent Province and, therefore, the soil water balance equation gives the crop water use as:

$$ET = -\Delta S + P + I \qquad (3)$$

Precipitation data (P) for Tashkent were taken from the Meteorological Station of the Institute, which is located at the Central Experiment Station. During the wheat experiment periods (October – June) precipitation was 249 mm and 716 mm in 2000-2001 and 2001-2002, respectively.

Values of change in soil water stored in the profile (ΔS) were calculated with the use of the integral calculus method and data from Table 4. Values of profile water content at the beginning of each growing season were similar in all treatments and so were lumped across treatments in Table 4.

Table 4. Volumetric water content of the old irrigated typical gray soil at the beginning and the end of vegetation (Tashkent, winter wheat)

Soil layer (cm)	Volumetric water content (m^3 m^{-3})									
	At the beginning of vegetation		At the end of vegetation							
			Experimental treatments (% of F_C)							
			65-65-70		70-70-60		75-75-60		80-80-70	
	2001	2002	2001	2002	2001	2002	2001	2002	2001	2002
30	0.250	0.225	0.174	0.284	0.205	0.275	0.202	0.283	0.205	0.282
50	0.250	0.273	0.206	0.290	0.206	0.277	0.240	0.275	0.230	0.283
70	0.250	0.274	0.215	0.271	0.233	0.286	0.250	0.279	0.251	0.284
90	0.260	0.263	0.232	0.277	0.240	0.284	0.248	0.283	0.272	0.294
110	0.250	0.260	0.275	0.279	0.265	0.282	0.275	0.288	0.300	0.295
130	0.270	0.274	0.288	0.286	0.262	0.287	0.294	0.289	0.307	0.290
150	0.290	0.259	0.309	0.287	0.277	0.290	0.296	0.288	0.320	0.299

Having calculated the ΔS for each treatment of the experiment, we determined the ET for the 0 to 150-cm deep soil control volume (Table 5):

Table 5. Water use (ET) of winter wheat in Tashkent

Treatment #	% of F_C treatments	ΔS (mm)		ET (mm)	
		2001	2002	2001	2002
1	65-65-60%	33.1	20.4	426	881
2	70-70-60%	28.2	21.2	453	885
3	75-75-60%	24.3	20.5	467	882
4	80-80-70%	21.5	22.0	492	899

Results of the experiments showed that top yields at both sites were reached for treatments 3 and 4, which were concluded as optimal and high moisture mode, respectively (Table 6). Treatments 1 and 2 were considered to be deficit scheduling of irrigations. Additional yield received (average for two years) at the optimal mode (75-75-60% of F_C) in comparison with the rigid scheduling of irrigation (65-65-60% of F_C) was: for Tashkent, 0.77 t ha^{-1} (19.5%); and for Syrdarya, 0.50 t ha^{-1} (13.8%).

Table 6. Irrigation and productivity of winter wheat at two locations in Uzbekistan

Treatment (% F_C)	Irrigation, (m^3 ha^{-1})		Grain Yield (t ha^{-1})		Water requirement per unit yield (m^3 t^{-1})		Irrigation water use efficiency (kg m^{-3})	
	2001	2002	2001	2002	2001	2002	2001	2002
Tashkent								
65-65-60	2100	1750	4.01	3.89	5.24	3.89	1.91	2.57
70-70-60	2320	1900	4.58	4.18	5.06	4.55	1.98	2.20
75-75-60	2420	1960	4.99	4.45	4.85	4.40	2.06	2.27
80-80-70	2650	2050	5.01	4.60	5.29	4.46	1.89	2.24
Syrdarya								
65-65-60	2810	880	3.60	3.65	7.80	2.41	1.28	4.15
70-70-60	3150	880	4.16	3.99	7.57	2.21	1.32	4.52
75-75-60	3230	880	4.26	3.99	7.58	2.21	1.32	4.52
80-80-70	3400	880	4.34	3.90	7.83	2.26	1.28	4.42

CONCLUSIONS

1. Results of our experiments with winter wheat carried out in two soils and climates of Uzbekistan have shown that water content of the soil profile could be rapidly and accurately measured by soil moisture neutron probe (SMNP). The SMNP allows study of water content dynamics of soil profiles, determination of concrete data on water use, and scheduling of irrigations during cropping seasons. For those soils where high water tables exist, use of the SMNP alone would not allow calculation of crop water use (ET). Weighing lysimeters or a numerical approach are needed.
2. The precision of calibration equations was acceptable for research objectives involving measurement of crop water use.
3. Experimental results of the two years of investigations showed that optimal development and high crop productivity of winter wheat at both project sites were reached when irrigations were scheduled at soil moisture levels of 75, 75, and 60% of field capacity during the three major crop growth stages, respectively. More irrigation did not result in additional yield from the crop.

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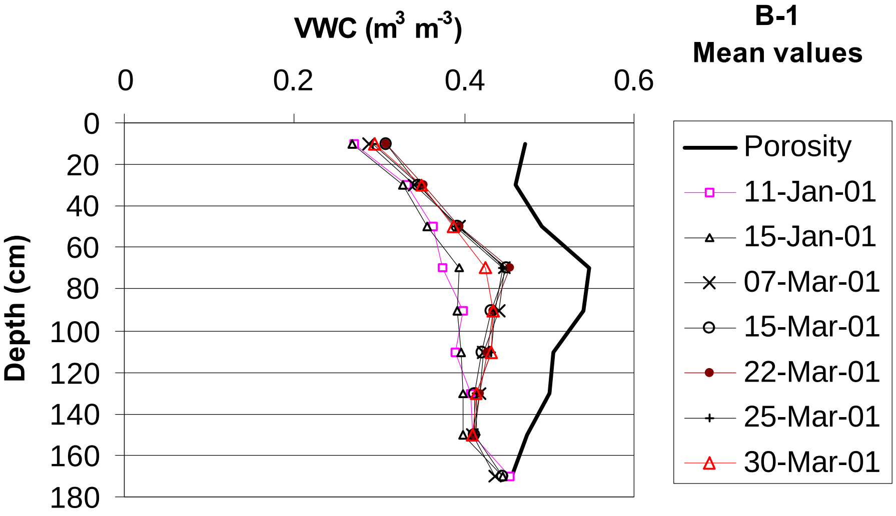

Figure 1. Evolution of profile volumetric water content (VWC) at the Syrdarya Branch Station in the winter wheat experiment, treatment B-1, showing that a water table existed at 170-cm depth. Mean of values from three access tubes.

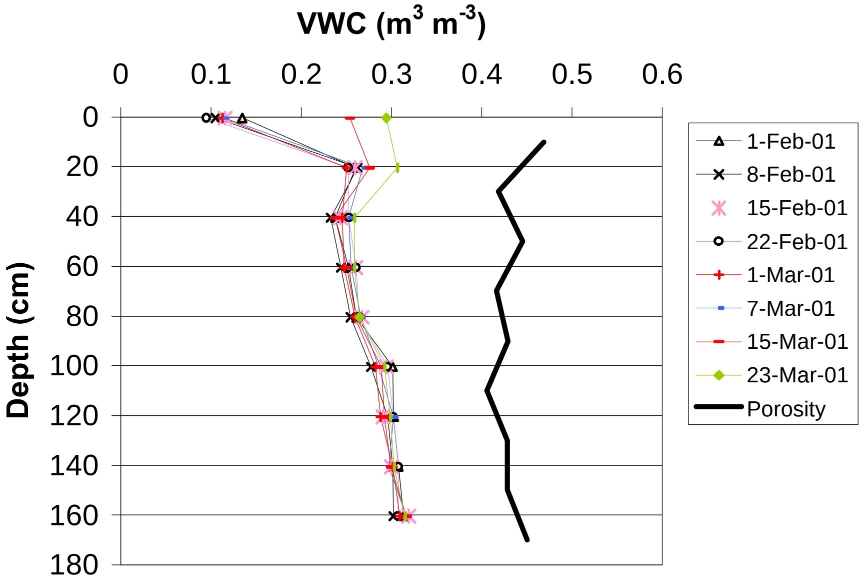

Figure 2. Evolution of profile volumetric water content (VWC) at the UNCGRI, Tashkent during the wheat irrigation season in 2001.