Water table contribution to alfalfa water use in different environments of the Argentine Pampas

Dardanelli, J. and D.J. Collino

SUMMARY

In the Argentine Pampas, although the water table is considered an important source of water supply for the alfalfa crop, it has not been previously quantified. The goal of this study was to estimate the water table contribution to alfalfa water use in several environments, using an indirect method derived from water use efficiency determinations. Data sets were obtained from experiments conducted for four growing seasons at four locations: Anguil, Rafaela, General Villegas and Manfredi. Water table contribution was estimated considering the crop water use efficiency and the water use from the upper layers (rainfall supplied). Capillary contribution from the water table was assumed, if the dry matter/water use from the upper layers ratio was higher than a given water use efficiency threshold. When present, the water table contribution varied among locations between 15 and 25% of the crop water use, and was not related to the groundwater depth. A pooled exponential relationship between the seasonal water table contribution and seasonal effective rainfall was determined.

Key Words: Alfalfa, water table, water use efficiency.

Dardanelli, J. and D.J. Collino, 2002. Contribución de la capa freática al consumo de agua de la alfalfa en diferentes ambientes de la región pampeana argentina. Agriscientia XIX: 11-18

RESUMEN

En la Región Pampeana Argentina, se considera a la capa freática como una importante fuente de agua para la alfalfa, aún cuando su aporte no fue previamente cuantificado. El objetivo de este estudio fue estimar la contribución de la napa freática al consumo de la alfalfa en diferentes ambientes, usando un método indirecto que utiliza mediciones de la eficiencia en el uso del agua. Los datos fueron obtenidos de cuatro años de experimentos, en cuatro localidades: Anguil, Rafaela, General Villegas y Manfredi. La contribución de la capa freática fue estimada considerando la eficiencia en el uso del agua del cultivo, y el consumo de agua de las capas superiores de suelo, (recarga dependiente de lluvias). Se asumió una contribución de la capa freática al consumo del cultivo cuando la

Fecha de recepción: 22/02/02; fecha de aceptación: 11/10/02

relación materia seca/consumo de agua de las capas superiores de suelo superó un valor umbral de eficiencia en el uso del agua. Este aporte varió entre localidades, entre 15 y 25% del agua consumida por el cultivo, y no estuvo relacionado con la profundidad de la capa freática. Se estableció una relación exponencial entre la contribución estacional de la capa freática y la precipitación efectiva estacional.

Palabras clave: Alfalfa, capa freática, eficiencia en el uso del agua.

J. Dardanelli, Estación Experimental Agropecuaria Manfredi - INTA. 5988 Manfredi, Córdoba. .Argentina. D.J. Collino, Instituto de Fitopatología y Fisiología Vegetal - INTA. Cno. 60 Cuadras Km 51/2, 5119 Córdoba. Argentina. E-mail: jdardanelli@correo. inta. gov.ar

INTRODUCTION

Alfalfa *(Medicago sativa* L.) is the most important forage crop in Argentina. There are approximately 7 million hectares (INDEC, 1996), mostly in the Pampas region. Due to its adaptability to different environments, excellent nutritional quality, and high forage yields, alfalfa is the base of the Argentinean milk and beef production. Average forage yields are between 10 and 18 t ha^{-1} $year^{-1}$ (Rossanigo, 1996), although a minimum value of 5 t ha^{-1} $year^{-1}$ (Rossanigo *et al.,* 1995) and a maximum value of 29 t ha^{-1} $year^{-1}$ (Rossanigo, 1996), have been reported. This high annual variability in forage production could be partially attributed to variable rainfall patterns (Hall *et al.,* 1992), causing periods with either, adequate or insufficient water balance.

Besides rainfall, water table contribution affects both the dry matter production and its annual variability. Although no previous studies of such contribution were reported for the Pampas region, it is possible to infer the water table influence on the dry matter production from previous field experiments. The average annual dry matter production reported in several experiments was significantly lower at Anguil (8 t ha^{-1} yr^{-1}), as compared to Marcos Juárez (20.5 t ha^{-1} yr^{-1}) (Spada, 1995, 1998, 2000, 2001). This marked difference in yield between both sites is not related only to their corresponding average rainfall annual values (710 mm for Anguil and 927 mm for Marcos Juárez). An extra contribution of water supplied by a shallow soil depth water table at Marcos Juárez might be supposed (D. Basigalup, 2001, pers. comm.). On the other hand, the dry matter production variation coefficient was lower at Marcos Juárez (20%) than at Anguil (40%), suggesting that the water table supply also decreased the interannual variability of forage crop production.

Several studies estimated the capillary contribution from a water table measured using lysimeters in which the water table depth was maintained at a fixed soil depth with a pipe connected to a Mariotte bottle (Benz *et al.,* 1982, Smith *et al.,* 1996, Kang *et al.,* 2001). Nevertheless, this technique can not be used under field conditions without disturbing the soil. The capillary contribution can be measured in a field experiment by estimation using the Darcy's law for steady state conditions (Singh & Kumar, 1993). To our knowledge, no previous studies about water table contribution to crop water use have been performed, using indirect methods derived from water use efficiency calculations. If we can distinguish soil layers where the soil water content is independently supplied by rainfall or water table, and the normal values of water use efficiency are known, it is possible to estimate the water table contribution to crop water use. Several alfalfa water use efficiency studies have been reported. Mean annual values fluctuate between 17 and 23 kg mm^{-1} (Wright, 1988; Grimes *et al.,* 1992; López *et al.,* 1997). The goal of this study was to estimate the water table contribution to alfalfa water use in several environments of the Argentina Pampas using an indirect method derived from water use efficiency determinations.

MATERIALS AND METHODS

Experimental data sets

Data sets were obtained from experiments conducted during four growing seasons (1993/94 to 1996/97) at four locations: Anguil, La Pampa (36°30'S; 63°49'W), Rafaela, Santa Fe (31°11'S;

61°33'W), General Villegas, Buenos Aires (34°54'S; 62°44'W) and Manfredi, Córdoba (31°49'S; 63° 48'W)

The soil at Anguil is a loamy Enthic Haplustoll (USDA Soil Taxonomy), with 2.7% organic matter in the upper 15 cm. At Rafaela the soil is a silty loam Typic Argiudol, with 3.3% organic matter in the upper 15 cm, while at General Villegas the soil is a loamy Typic Hapludoll, with 2.3% organic matter in the upper 12 cm. The soil at Manfredi is a silty loam Enthic Haplustoll with 1.7% organic matter in the upper 20 cm. None of the soils presented physical restriction for root development and for upward or downward water flux.

The lower limit *(LL,* cm^3 cm^{-3}), for each soil layer was obtained from previous field experiments using (*i*) soil water data measured during the growing season, (*ii*) laboratory measurements at -1.5 MPa, when the *LL* was not achieved during the season, or (*iii*) by extrapolating the *LL* from values found at shallower depths if the soil properties were similar for the deeper layers. The drained upper limit *(DUL,* cm^3 cm^{-3}), was obtained from previous field experiments and the volumetric water content at saturation *(SAT,* cm^3 cm^{-3}), was determined in the laboratory or estimated from soil properties. The bulk density *(BD,* g cm^{-3}), was measured using the Blake & Harge (1986) technique. The *LL, DUL, SAT* and *BD* values for different soil layers within each site are shown in Table 1.

Alfalfa *(Medicago sativa* L.) was sown during the 1993 fall season. Sowing dates were 29 March, 15 April, 26 April and 31 March, at Anguil, Rafaela, General Villegas and Manfredi, respectively. Two varieties, Monarca SP INTA (non-dormant) and Victoria SP INTA (moderately dormant), with a 300 pl m^{-2} and 0.2 m row spacing, arranged in a complete randomized design with five replications were used. Plot size was 6 m wide by 14 m long.

Table 1: Lower limit *(LL,* cm^3 cm^{-3}), drained upper limit *(DUL,* cm^3 cm^{-3}), volumetric water content at saturation *(SAT,* cm^3 cm^{-3}) and bulk density *(BD,* g cm^{-3}), at different locations and layers.

Site	Layer depth	***LL***	*DUL*	*SAT*	***BD***
Anguil	0-20	0.098	0.243	0.330	1.11
	20-40	0.105	0.262	0.320	1.17
	40-60	0.090	0.250	0.320	1.13
	60-80	0.086	0.248	0.320	1.15
	80-200	0.081	0.242	0.320	1.18
Rafaela	0-15	0.177	0.338	0.474	1.18
	15-24	0.170	0.338	0.474	1.26
	24-32	0.170	0.334	0.474	1.33
	32-55	0.225	0.375	0.445	1.38
	55-87	0.252	0.392	0.445	1.35
	87-115	0.236	0.384	0.445	1.31
	115-140	0.228	0.368	0.423	1.28
	140-180	0.200	0.340	0.423	1.27
Gral. Villegas	0-20	0.110	0.270	0.380	1.20
	20-40	0.098	0.250	0.340	1.31
	40-60	0.082	0.210	0.300	1.23
	60-300	0.072	0.205	0.300	1.20
Manfredi	0-20	0.110	0.321	0.550	1.22
	20-40	0.108	0.290	0.510	1.20
	40-680	0.094	0.244	0.445	1.20

Daily weather measurements (maximum and minimum air temperature, relative sunshine fraction, wind speed and relative humidity) were recorded at sites between 500-2000 m from the experimental plot area. The solar radiation was estimated from the relative sunshine fraction. Daily precipitation was measured close to the experimental plots. The crop potential evapotranspiration *(ETc,* mm), was obtained by multiplying the reference evapotranspiration calculated using the Penman-FAO method (Doorenbos & Pruit, 1977) by the crop coefficients found in previous experiments for the same varieties under study (López *et al.,* 1997).

Crop measurements

Above-ground biomass was harvested from 1 m^2 samples, when the **first** flowers appeared (10% flowering) or when new crown shoots reached 5 cm height. Plant material was oven-dried at 70°C until constant weight was achieved, to obtain the dry matter (*DM*, kg ha^{-1}).

Soil water content was measured in each plot at sowing and close to each cutting date during the season. The gravimetric technique was used at General Villegas and Manfredi. The neutron probe technique was used at Anguil and Rafaela, except at 0-20 cm upper layer where the gravimetric technique was employed. In all locations the measurements were taken at 20-cm in depth intervals down to 2.0, 1.8, 3.0 and 6.8 m at Anguil, Rafaela, General Villegas and Manfredi, respectively. To determine volumetric water content, *BD* (obtained "in situ"), was used. The maximum depth of measurement was set at layers with high volumetric water contents (over the *DUL),* indicating that the water table was close to those layers. No influence of water table was detected at Anguil, and the soil water content remained close to the *LL* below 2 m soil depth, because the rainfall was not enough to refill the soil profile. Consequently, data presented for Anguil reach only 2 m depth.

The crop water use, when no water table contribution was present *(WU_1*300 mm), was determined from the water balance among successive water content measurements using the following equation:

$$WU_1 = P_{eff} + DS \qquad [1]$$

where, P_{eff} (mm) is the water supply by effective rainfall and *DS* (mm) is the change in stored water within the whole soil profile. Each daily effective rainfall value was calculated using the following equation proposed by Dardanelli *et al.* (1992) for a silty loam soil:

$$P_{eff} = 2.43 Pr^{0.667} \qquad [2]$$

where, *Pr(mm)* is the daily precipitation. Water losses by drainage below the root zone were non-significant. Eq. [2] was considered applicable to all sites, because the soils present similar soil surface textures (loam to silty loam).

Water use efficiency *(WUE,* kg mm^{-1}), for each interval between cuttings, (when not water table contribution was present), was determined using the following expression:

$$WUE = \frac{DM}{WU_1} \qquad [3]$$

Water table contribution estimation

The water table contribution to the crop water use at Manfredi, Rafaela and Villegas was indirectly estimated for each interval between cuttings considering the crop water use efficiency and the water use from the upper layers (rainfall supplied). When the water table was present, the amount of crop water use resulted from the sum of water supplied by the rainfall, and the capillary contribution from the water table. In this study, it was possible to differentiate two groups of layers in the soil profile: the upper one, where the water stored in the soil was supplied by rainfall, and the lower group of layers, where the soil water was supplied by the capillary contribution from the water table. Between the above mentioned groups of layers, an intermediate one was observed showing little changes in water content and moisture values close to the *LL.* Figure 1 illustrates an example for General Villegas, where the upper group of layers included 0 to 120 cm, and the lower group 150 to 300 cm. Between both groups, at 120 to 150 cm, the volumetric water content remained fairly constant and close to the *LL* during the growing cycle. It was assumed that the water content fluctuations at 0-120 cm were caused mostly by rainfall input and root water uptake, while between 150-300 cm, water content progressively increased with depth up to values greater than the *DUL* and close to *SAT,* due to the water table influence. The water table depth was assumed to be approximately 80 cm below the depth at which *DUL* values were found according to Kang *et al.* (2001) findings. At General Villegas, water use from the upper group of layers *(WU_{ul},* mm) was calculated using Eq. [1], but considering only the 0-150 cm soil depth. Using the same criteria, the WU_{ul} at Rafaela and Manfredi was calculated considering 0-100 and 0-300 cm soil depths, respec-

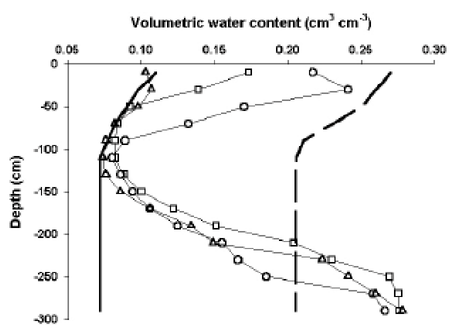

Figure 1: Volumetric water content at different soil depth and dates: 12/06/94 (O), 1/06/95 (☐) and 1/30/95 (△). Solid line indicates the lower limit and dashed line indicates the drained upper limit.

tively. As discussed for Villegas, WU_{ul} could be calculated at Rafaela and Manfredi because both sites presented volumetric water contents that remained fairly constant and close to the *LL* during the growing cycle, at 70 to 100 cm and 120 to 300 cm, respectively. Once WU_{ul} was obtained, a dry matter/WU_{ul} ratio value was calculated for each cutting. Values between Monarca sp INTA and Victoria sp. INTA pooled *WUE* range of values (previously reported), and below a critical threshold, indicated that no water table supply contributed to crop water use. Conversely, when the dry matter/WU_{ul} ratio values were higher than a critical threshold, we assumed a water table contribution to crop water use. The critical threshold was calculated from average seasonal *WUE* values reported by López *et al.* (1997) plus three standard deviations. Those average seasonal *WUE* values were 22.3 and 14.8 Kg mm^{-1} for spring-summer and fall-winter, respectively. As a result of the sum of each average seasonal *WUE* plus three standard deviations, two critical threshold values were obtained for spring-summer and fall-winter cuttings: 33.2 and 23.8 kg mm^{-1}, respectively.

When the water table contributed to crop water use, WU_{wt},mm was calculated as:

$$WU_{wt}=\left(\frac{DM}{WUE_S}\right)-WU_{ul} \qquad [4]$$

where, WUE_S (kg mm^{-1}) is the average seasonal water use efficiency (López *et al.,* 1997). Crop water use including water table contribution *(WU_2),* was calculated as:

$$WU_2=WU_{ul}+WU_{wt} \qquad [5]$$

The growing season water use resulted from the sum of water use for each cutting obtained using Eq. [5] (with water table contribution), or Eq. [1] (without water table contribution). The crop water deficiency was determined for each growing season as the difference between the growing season water use and the *ETc.*

RESULTS AND DISCUSSION

The water content above the lower limit at different sites and depths for selected dates is shown in Figure 2. Three groups of layers within the soil profile were present at Rafaela, General Villegas and Manfredi: an upper group where the available water was supposed to be mostly supplied by rainfall; an intermediate group where soil water remained fairly constant and close to the *LL* during the growing

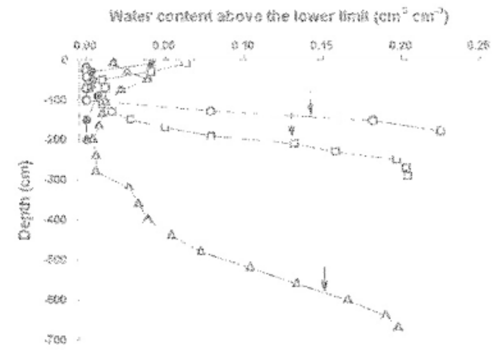

Figure 2: Volumetric water content above the lower limit (cm^3 cm^{-3}), for selected dates at Anguil (●), Rafaela (O), General Villegas (□) and Manfredi (△). The arrows indicate the depth at which the drained upper limit was achieved.

cycle, and a lower group of layers, where the soil water was supposed to be mostly supplied by the capillary contribution from the water table. At Anguil, water table influence was absent and the volumetric water content was close to the LL at the deepest soil layers, where the rainfall contribution was negligible. Since *DUL* values were reached at different soil depths, water table depths were different among locations. Assuming that the water table depth might be 80 cm below the depth at which the DUL was observed, we could deduce that water table depths were different among locations: 225, 290 and 600 cm at Rafaela, General Villegas and Manfredi, respectively. These differences corresponded to selected dates (approximately two years after sowing). The ranking among locations remained constant during most of the growing period. Periodically, water table depth observations were made contemporary to the alfalfa growing cycle at the Rafaela and Manfredi meteorological stations (close to the experimental sites). The depth of the water table fluctuated between 205 and 350 cm at Rafaela and between 480 and 680 cm at Manfredi. No observations were available for Villegas, although Díaz Zorita (pers. comm.), estimated that water table level was at 300 to 400 cm at the experimental area, during the first part of the crop growing period.

Considering individual cuttings at the General Villegas site, when the water table influenced the crop water use, the dry matter/WL_{ul} ratio was significantly higher than the average seasonal *WUE.* When the dry matter/Wl_{ul} ratio was below that of the critical threshold, this ratio was the *WUE (Fig.* 3A). Volumetric water content values corresponding to the *DUL were* found at measured depths until the 18th

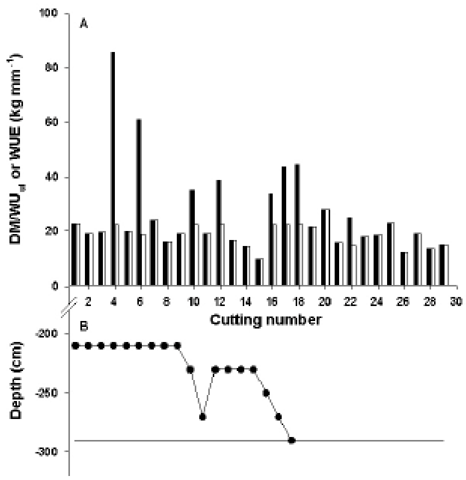

Figure 3: (A): Dry matter/upper layers water use ratio *(DM/WU*ul, Kg mm^{-1}) closed bars, and water use efficiency (*WUE,* Kg mm^{-1}), open bars, and (B): depth at which the volumetric water content corresponding to the drained upper limit *(DUL)* was found, at General Villegas site.

cutting (Fig. 3B). However, only in some cuttings, differences between the dry matter/*WU*ul ratio and the *WUE* were observed. During the first part of the growing cycle (cuttings 1st to 3rd), the crop used the water stored in the upper soil layers. From the 4th to the 18th cutting, only when rainfall shortage occurred, the crop used groundwater. Benz *et al.* (1983) reported that the water table makes a sizable contribution to actual alfalfa evapotranspiration when the irrigation level decreases. Since the 19th cutting on, the volumetric water content values remained below the *DUL* in the measured layers. Nevertheless, the 22nd cutting showed water table influence, probably because the root system was capable to extract water at deeper layers where measurements were taken. At the end of the growing cycle, no other water table contributions were observed, suggesting that the groundwater was not present at depths where the root system was developed.

In every location, the *WUE* of individual cuttings varied between 10 and 32 Kg mm^{-1}. These values are close to those reported by Guitjens (1990), who found a range from 6 to 30 Kg mm^{-1}.

When present, the water table contributed to the crop water use every growing season (Table 2), with percentages ranging from 3% (Rafaela, 93/94 growing season), to 40% (Rafaela, 96/97 growing season). At Manfredi, no water table contribution was observed during the 93/94 growing season. It was probably because the root system was not deep enough to uptake water from the water table, which was located at considerable depth, according to the *DUL* depth fluctuations (between 550 and 650 cm). In fact, Borg & Grimes (1986) reported that the expected maximum rooting depth in alfalfa is 180 to 240 cm during the first harvesting season. In subsequent growing seasons, water table contributions were observed at Manfredi, in agreement with Borg & Grimes (1986), who reported an expected maximum rooting depth between 300 and 600 cm since the second growing year. The percent contributions of the water table, excluding the growing seasons in which the root system was not deep enough to uptake groundwater, were 15, 22 and 25, at General Villegas, Rafaela and Manfredi, respectively. Moreover, in studies using lysimeters, Smith *et al.* (1996), found a 40% capillary contribution to the water use, which is not far from our results.

In our study, the water table contribution to the water use was not related to the groundwater depth and, therefore, a pooled relationship between the seasonal water table contribution and seasonal effective rainfall, was found (Fig. 4). The exponential function obtained indicates that, when the effective rainfall decreases, the contribution of the water table increases exponentially. Conversely, when the effective rainfall increases, this contribution tends to be negligible, although the water use does not match the crop potential evapotranspiration. The efficiency of the water table as a water source was lower than rainfall or irrigation, because these wet the upper soil layers, where more density of roots is expected. For example, at Rafaela, where the water table was closer to the soil surface (225 cm) and was present during the whole growing cycle, the water use/crop potential evapotranspiration ratio was only 0.58 (Table 2). The average dry matter annual production

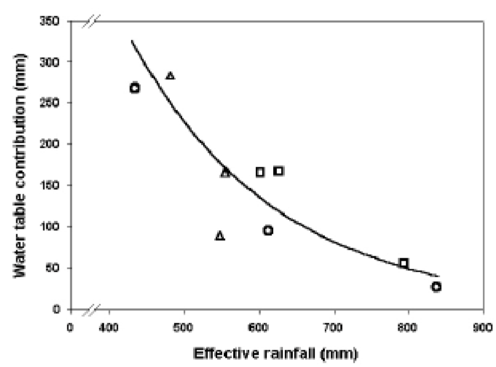

Figure 4: Relationship between the water table contribution to crop water use (mm growing season^{-1}), and the effective rainfall (mm growing season^{-1}), obtained using data from Rafaela (O), General Villegas (□) and Manfredi (△). Fitted line was $y=2727.9e^{-0.0051x}$; r^2=0.81.

Table 2: Number of cuttings, dry matter production, effective rainfall, water use, water table contribution, crop potential evapotranspiration (ETc), water use/ETc ratio, water deficiency and water use efficiency (WUE), for all growing seasons and sites.

Site	Growing season	Number of cuttings	Dry matter kg ha^{-1}	Effective rainfall mm	Water use mm	Water table contribution mm	ETc mm	Water use/ETc	Water deficiency mm	WUE Kg mm^{-1}
	93/94	4	12,544	616	703	0	1,460	0.48	-753	17.8
Anguil	94/95	8	9,325	594	564	0	1,602	0.35	-1,019	16.5
	95/96	7	10,969	579	573	0	1,434	0.40	-845	19.1
	96/97	4	12,741	779	750	0	1,464	0.51	-722	17.0
	Sum	23	45,578	2,569	2,590	0	5,960	0.43	-3,338	17.6
	93/94	7	18,954	837	868	28	1,428	0.61	-561	21.8
Rafaela	94/95	8	19,866	620	965	340	1,526	0.63	-562	20.6
	95/96	8	16,056	612	872	96	1,510	0.58	-638	18.4
	96/97	8	13,533	433	677	269	1,411	0.48	-734	20.0
	Sum	31	68,409	2,502	3,381	733	5,875	0.58	-2,494	20.2
	93/94	7	17,479	601	836	166	1,369	0.61	-533	20.9
Villegas	94/95	7	16,168	793	890	56	1,369	0.65	-479	18.2
	95/96,	8	16,723	626	826	168	1,499	0.55	-673	20.3
	96/97	7	12,589	572	643	0	1,484	0.43	-841	19.6
	Sum	29	62,960	2,591	3,196	390	5,720	0.56	-2,525	19.7
	93/94	6	14,082	600	760	0	1,419	0.54	-655	18.5
Manfredi	94/95	6	15,654	481	757	282	1,476	0.51	-719	20.7
	95/96	7	15,606	554	670	164	1,283	0.52	-613	23.3
	96/97	8	13,821	548	723	88	1,527	0.47	-804	19.1
	Sum	27	59,163	2,183	2,910	533	5,705	0.51	-2,791	20.3

(17.1 t ha^{-1} yr^{-1}) was considerable lower than the 28.3 t ha^{-1} yr^{-1} potential production reported by López *et al.* (1997) for the same varieties under irrigated conditions.

The lack of relation between the water table contribution and the water table depth does not agree with previous studies. Tovey (1969) found progressive reductions of water table contribution from 0.6 to 2.4 static water table depths. A similar trend was reported by Benz *et al.* (1983), in the range of 46-210 cm. Khang *et al.* (2001), found that the capillary contribution on wheat and maize decreased from 120 to 250 cm. This disagreement with previous reports could be explained because in our study the water tables were deeper (225 to 680 cm). To our knowledge, no previous studies on the water table contribution in alfalfa water use were made when water tables were situated deeper than 250 cm. Our results demonstrate that the alfalfa root system is able to uptake water from several meters deep in the soil.

An increase in *WUE* is expected when the water table contributes to the crop water use because this source of water has no soil evaporation losses. Consequently, the *WUE* values observed at Rafaela, General Villegas and Manfredi (approx. 20 kg mm^{-1}) were higher than Anguil value (17.6 Kg mm^{-1}) (where the water table did not influence the water use), and greater than the 18.6 kg mm^{-1} obtained in a previous study carried out under irrigated conditions, using the same varieties (López *et al.,* 1997).

In brief, the water table contribution varied among locations between 15 and 25% of the crop water use, and was not related to the groundwater depth. A pooled exponential relationship between the seasonal water table contribution and effective rainfall was obtained. This relationship could be used as a predictor of the annual water table contribution, when the effective rainfall is known and the water table is present in the soil within a wide range of depths (water content at *DUL* values at depths between 225 and 600 cm).

ACKNOWLEDGMENTS

The authors thank Dr. Leonardo Gómez for English language revision, and are grateful to the staff of the INTA-National Alfalfa Project, PRONALFA, for contributing with data sets.

REFERENCES

Benz, L.C.; E.J. Doering, and G.A. Reichman. 1982. Water table management saves water and energy. Transactions of the ASAE 24(4): 995-1001.

Benz, L.C.; E.J. Doering, and G.A. Reichman. 1983. Controlled water table and irrigation effects on alfalfa evapotranspiration in sandy soils. ASAE Summer Meeting, Montana State University. Paper Nº 83-2063.

Blake, G.R and K.H. Harge. 1986. Bulk Density. In: A. Klute (ed.). Methods of Soil Analysis. Part 1 Physical and Mineralogical Methods 2th Ed. Soil Science Society of America. Madison, Wl. pp. Blake, G.R and K.H. Harge. 1986. Bulk Density. In: A.Klute (ed.). Methods of Soil Analysis. Part 1 Physical and Mineralogical Methods 2th Ed. Soil Science Society of America. Madison, Wl.

Borg, H. and D.W. Grimes. 1986. Depth development of roots with time: An empirical description. Trans. ASAE. 29:194-196.

Dardanelli, J. L; A.C. De la Casa; M.R. Ateca; R. Zanvettor; F. Nuñez Vázquez y H.P. Salas. 1992. Validación del balance hidrológico versátil para la sucesión sorgo-soja bajo dos sistemas de labranza. En: Revista Agropecuaria de Manfredi y Marcos Juárez (Argentina). 7(2): 20-29.

Doorenbos, J. and W.O. Pruitt. 1977. Guidelines for predicting crop water requirements. FAO Page 24. (Revised). Rome.

Grimes, D.W.; P.L. Wiley and W.R. Sheesley. 1992. Alfalfa yield and plant water relations with variable irrigation. Crop Sci. 32:1381-1387.

Guitjens, J.C. 1990. Alfalfa. In: B.A. Stewart and Nielsen, D.R. (Eds.). Irrigation of agricultural crops. Agronomy Monograph Nº 30. ASA-CSSA-SSSA, Madison, Wi. pp. 537-568.

Hall, A.J.; C.M. Rebella; C.M. Ghersa and J. Ph. Culot. 1992. Field-crop systems of the Pampas. In: Pearson, C.J. Ed. Ecosystems of the world: field crop ecosystems. Elsevier, Amsterdam, pp. 413-449.

INDEC 1996. Censo Nacional Agropecuario.

Khang, S.; F. Zhang; X. Hu; P. Jerie and L. Zhang. 2001. Effect of shallow water table on capillary contribution, evapotranspiration, and crop coefficient of maize and winter wheat in a semi-arid region. Aust. J. Agric. Res. 52:317-327.

López, A.; J.L Dardanelli; D.J. Collino; R. Sereno y R.W. Racca. 1997. Efecto del grado de reposo invernal sobre la producción, consumo y eficiencia en el uso del agua en alfalfa cultivada bajo riego RIA 28(2): 41-48.

Rossanigo, R. 1996. Red de evaluación de cultivares de alfalfa. INTA. In.: Agromercado, p. 21.

Rossanigo, R. O., M. del C. Spada y O. A. Bruno. 1995. Evaluación de cultivares de alfalfa y panorama varietal en la Argentina. In: E. H. Hijano y A. Navarro (ed). La Alfalfa en la Argentina. INTA. Enc. Agro de Cuyo, Manuales, Nª 11. Editar, San Juan, Argentina.

Singh, P. and R. Kumar. 1993. Evapotranspiration from wheat under a semi-arid climate and a shallow water table. Agric. Water Management. 23: 91-108.

Smith, D.J.; W.S. Meyer; H.D. Barrs and S. Schwanberger. 1996. Lucerne daily water use and capillary upflow using weighing lysimeters: effect of soil type and groundwater salinity. CSIRO Division of water resources, Technical Memorandum, 96/6.

Spada, M. del C.(ed) 1995. Avances en alfalfa. Año 5, Nº 5. EEA Manfredi, INTA. 39 pp.

Spada, M. del C.(ed) 1998. Avances en Alfalfa. Año 8 Nº 8. EEA Manfredi, INTA.78 pp.

Spada, M. del C. (ed) 2000. Avances en Alfalfa. Año 10 Nº 10. EEA Manfredi, INTA.64 pp.

Spada, M. del C.(ed) 2001. Avances en Alfalfa. Año 11 Nº 11. EEA Manfredi, INTA.36 pp.

Tovey, R. 1969. Alfalfa water table investigations. J. Irrig. Drain. Div. Am. Soc. Civ. Eng. 95(IR4): 525-535.

Wright, J.L. 1988. Daily and seasonal evapotranspiration and yield of irrigated alfalfa in southern Idaho. Agron. J. 80: 662-669.