Soil water balance approach in crop water requirement studies

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INTRODUCTION

Water is one of the most important input required in agricultural production. Over 90 % of fresh biomass is essentially water which complements carbon dioxide as a major substrate in carbon fixation, photosynthesis, a process which is the essence of life on earth. Water requirement of plant growth is met from soil water stored within plant root zone. In temperate and tropical regions of high rainfall, soil water is continuously replenished as is depleted by plant growth. In such regions therefore scarcity of water, limiting agricultural production, is a rare occurrence. However, in arid and semiarid regions, or in areas of low and erratic rainfall which comprise one third of the global land area, available water resources must be sparingly and effectively used not only to ensure good crops but also to meet municipal and industrial water needs. Therefore under the conditions of highly variable climatological environment and chronically deficit rainfall of the arid zones, sustainable food security can not be obtained if the agricultural practices do not address to the effective usage of the most precious and yet uncertain resource, water.

Irrigation is one of the means available for maintaining optimum levels of soil water within the plant root zone. Although it is difficult to quantify share of irrigated agriculture in overall crop-yield increases achieved during the last quarter of the XX. Century,.Rangeley (1990) suggests that 70 % of the increase could be attributed to expansion of irrigation. Therefore investments for irrigation are of top priority in all countries of arid and semi-arid regions where agricultural sector uses main share of the available water resources (Table 1). However it has become a matter of serious concern in recent years that the performance of many irrigation projects has not been fully attained. Low irrigation efficiencies and excess water application in the fields compounded with seepage of water along the irrigation networks caused rising of ground water table, which in turn, triggered soil salinity problem in irrigated areas. As a result, much less area was often irrigated than actually planned, and therefore anticipated crop yield increases could not be achieved. Thus, agricultural scientists, particularly in arid and semiarid regions, need to develop new irrigation technologies which would sustain soil productivity and thereby attain high crop yields under irrigation.

While irrigation practices should be improved to sustain soil productivity under irrigated agriculture, different cropping systems and tillage practices should be tested for increased crop yields through improved soil water conservation and rain harvesting. The measurement and management of soil water in agricultural areas are therefore of great importance for monitoring of existing farming practices and water management, under both irrigated and rainfed conditions, to increase effective usage of available water resources. Accumulation of salts, frequently accompanied by drainage problem, is among the potential risks of endangering sustainability of irrigated agriculture. While plants transpire water, salts in the soil solution are left behind and accumulate. Salt concentrations may reach to such levels with time that they hinder plant growth and thereby crop yields decrease. Historical records for the past 6000 years show numerous examples of lost civilizations who failed to sustain soil fertility under irrigation as a result of salinity and lack of drainage. One of the most publicized example is the ancient Mesopotamia, presently Iraq, where flooding, seepage, over-irrigation and siltation lead to excessive soil salinity in lower delta plains of Euphrates and Tigris (Gelburd, 1985).

The proper design and management of irrigation schemes, as to ensure sustainability of soil fertility, requires a thorough knowledge of crop water requirement and good understanding of interactions of irrigation practices with soil. It is imperative to maintain a good water and salt balance to ensure a sustained soil productivity under irrigated agriculture. This chapters will review main components of water balance for *in situ* measurement of crop water requirement.

***Table 1** - Sectorial uses of available water resources (The World Bank, 1992).*

	Sectorial share of total water resources, %		
Country group	Agriculture	Municipal	Industry
Low and middle income	85	7	8
Sub-saharan Africa	89	8	3
East-Asia and Pacific	86	6	8
South Asia	94	3	3
Europe	45	14	41
Middle East & North Africa	89	6	5
Latin America & Caribbean	72	16	12
High income	39	14	47
OECD members	39	14	47
Other	67	22	11
World	69	9	22

WATER BALANCE

In plant water consumption studies, water balance approach is the simplest method used to estimate in-situ measurement of crop water requirement. Fig. 1 describes the main components of the water balance equation

$$I + P - (D + ET) - R = \pm \Delta S \quad (1)$$

where I, P and R representing irrigation, precipitation and runoff, can easily be assessed; D and ET are drainage and evapotranspiration terms respectively; R is runoff which can easily be measured if it can not be prevented, and ΔS is the change in plant root zone soil water storage. Equation (1) can conveniently be used to estimate ET if other terms are known. Soil water storage S can be measured using the equation

$$S = \int_{0}^{Z=L} \theta dz \approx \sum_{i=1}^{n} \bar{\theta} \Delta z \quad (2)$$

where θ is volumetric water content ($cm^3\ cm^{-3}$) measured at different depths over the plant rooting zone of L (Fig. 1). There are numerous methods available to measure soil water content.

The drainage term D in the water balance equation is the most difficult term to measure. It requires firstly measurement of water flux q (LT^{-1}) below the rooting depth (Z=L), which is defined by Darcy's equation as

$$q = -K(\theta)\nabla H \quad (3)$$

where $K(\theta)$ is unsaturated hydraulic conductivity (LT^{-1}), and ∇H is hydraulic gradient which can be assessed with tensiometers. If one knows water flux q (LT^{-1}) or Darcian flow rate, drainage term D can be calculated using the equation

$$D = \int_{t_1}^{t_2} q dt \quad (4)$$

for the time period from t_1 to t_2. The major difficulty in estimation of D stems from the uncertainty in experimental assessment of water flux which is very sensitive to errors made in measurement of $K(\theta)$ relation. A step-to-step method for field measurement of $K(\theta)$ is described in the following sections. Firstly however, basic methods describing estimation of ET under different conditions will be discussed.

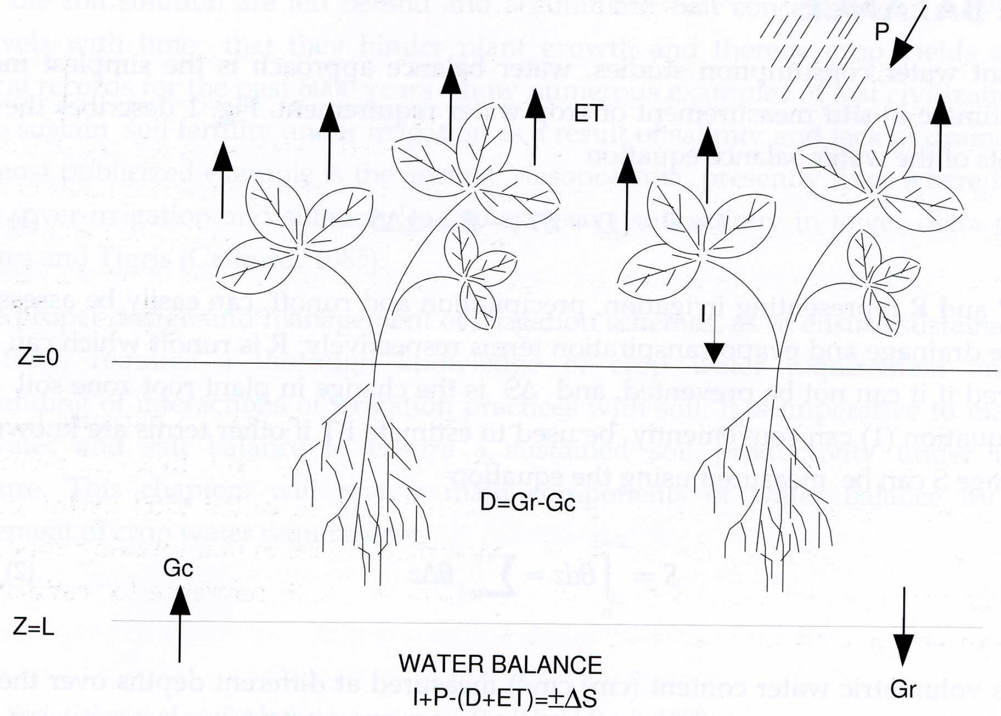

Fig. 1 - Main component of the water balance Equation (1).Gc is ground-water contribution to crop water consumption; Gr *is deep percolatiom.*

Conditions where Drainage can be Ignored

In situations where soil water content below plant rooting zone remains at very low values, the drainage term D in Equation [1] can be assumed as zero. In this case plant water consumption simply equals to changes of soil water storage during the time period considered, and can be calculated using

$$ET = [S(t_1) - S(t_2)] + I \quad (5)$$

which only requires soil water depletion profiles, covering plant rooting depth at different times. Data for water depletion profiles can be obtained with any convenient method used to measure soil water content. This approach is well adapted to arid and semi-arid regions. In high rainfall areas of humid and sub-humid regions, the assumption of no-drainage below the rooting zone may not be hold and therefore the method can not be used in such areas.

Conditions of Significant Drainage or Capillary Rise

In areas of high rainfall, such as humid and sub-humid regions, or in areas under irrigated agriculture, the drainage component of the water balance equation may be significantly high and therefore it can not be assumed zero. In such situations, the Equation [4] must be used to estimate the drainage term D. Although there is no limit for the application of the method, one must note that K(θ) relation must be available before hand to calculate the Darcian water flow rate through using Equation [3]. An other constraint to accurate estimation of D through Darcian water flow rate is that it is very sensitive to errors on θ.

In addition to data on water depletion, one needs tensiometers to measure hydraulic gradient ∇H around plant rooting depth (i.e., Z=L) to calculate water flux and thereby the drainage term. Tensiometers must be installed to establish so called total hydraulic head distribution of soil water along the soil profile, particularly close to plant rooting zone. There are three situations which are worth to discuss separately with reference to estimation of the drainage term in the water balance equation.

Existence of Zero Flux

In situations where plant rooting depths are very shallow or when one deals with evaporation alone from bare soil, or if there is no rainfall or irrigation during periods of measurement, existence of so called *zero flux plane* just below the rooting depth can easily be demonstrated with tensiometer data (Fig. 2). In such a situation, change in soil water storage during a given time period Δt above the zero flux plane is simply equal to ET or evaporation E if there is no plant. The fact that hydraulic gradient at a depth where zero flux exists (Zo) is zero implies that flux at that depth must be zero. Equation describing crop water consumption during the period from t_1 to t_2 therefore reduces to

$$ET = I + P + \Delta S\Big|_{Zo}^{0} - R \qquad (6)$$

where $\Delta S\Big|_{Zo}^{0}$ is change of soil water storage in a given time period Δt (Fig. 2).

Deep Percolation

Deep percolation of water or drainage (D) in high rainfall areas of humid and sub-humid regions and in areas under irrigation is very common. Estimation of drainage is an easy task if one has data on water depletion profiles, complemented with tensiometer data describing soil water hydraulic gradient below the rooting depth (Fig. 3). In such situations, the main difficulty is the measurement of water flux q using Equation [3]. If the field sites are properly equipped with tensiometers and K(θ) relation is available for the experimental soil, then measurement of water flux is not difficult, and it can be measured throughout the growing season at convenient intervals.

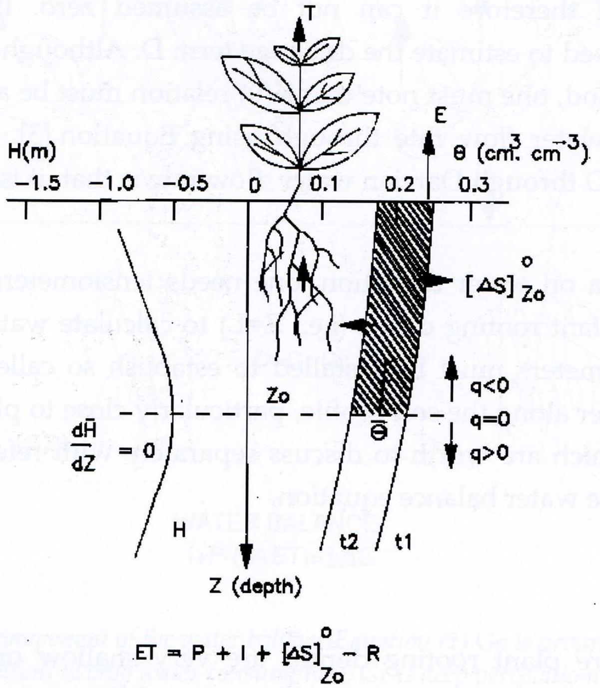

Fig. 2 - Zero flux plane at depth Zo blow the active roots where water flux is essentially nil.

Crop water consumption under situations where there is drainage can be calculated using Equation (1) arranged as

$$ET = I + P + \Delta S|_{Zo}^{0} - \int_{t_1}^{t_2} q dt - R \qquad (7)$$

Capillary Rise from Shallow Water Table

In the areas where water table is very close to soil surface, it is very likely that plants growing in such areas can benefit from water coming to plant rooting zone from the shallow water table through a phenomenon so called *capillary rise* which can be treated as negative drainage where water flow is in upward direction (Fig. 4). The last equation can be modified as

$$ET = I + P + \Delta S|_{Zo}^{0} + \int_{t_1}^{t_2} q dt - R \qquad (8)$$

to use in estimation of crop water requirement (ET) in areas where capillary rise is an important magnitude.

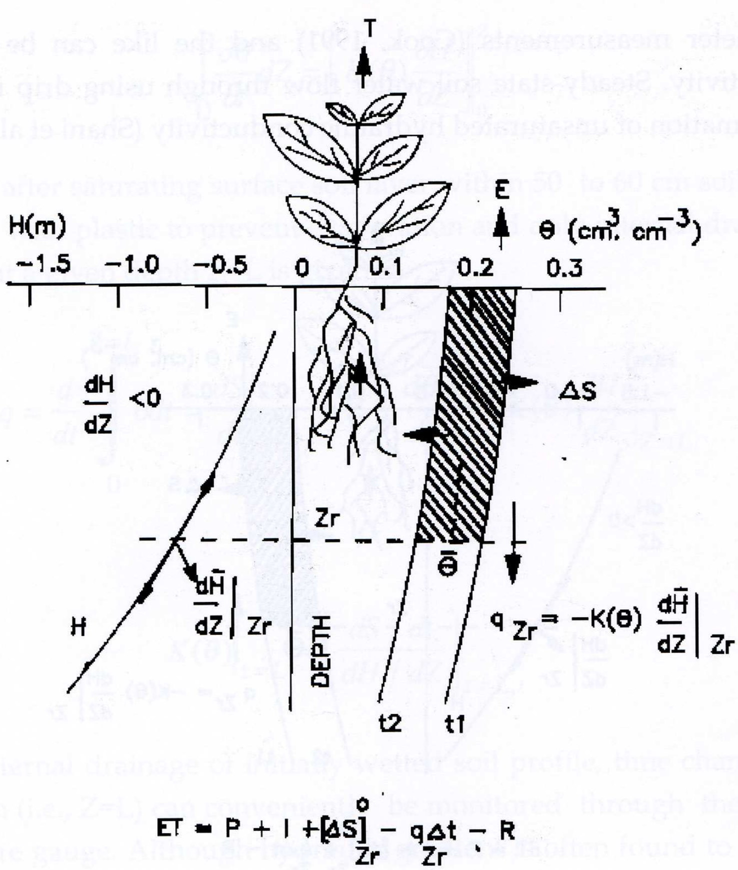

Fig. 3 - Components of water balance equation when deep percolation (i.e., Gr>Gc) is significant.

Measurement of Unsaturated Hydraulic Conductivity

There is increasing interest in determining flux of water through soils since it is an important element of water budget from both agricultural point of view and in environmental issues. Unsaturated hydraulic conductivity is the most important soil physical property describing water transport ability of soils, which in turn controls the rate of transport of dissolved chemicals in soils. Numerous measurements of hydraulic conductivity with due consideration of spatial variability of soils in this property may be essential however to characterise field soils (Nielsen et al., 1973).

Theory

There are numerous laboratory and field methods available to measure unsaturated hydraulic conductivity of soils. Soil water retention data (Talsma, 1985), particle size distribution of field soils (Schuh and Sweeney, 1986), ring infiltrometers (Youngs, 1987), suction permeameter measurements (Cook, 1991) and the like can be used to estimate hydraulic conductivity. Steady-state soil water flow through using drip irrigation can also facilitate field estimation of unsaturated hydraulic conductivity (Shani et al., 1987).

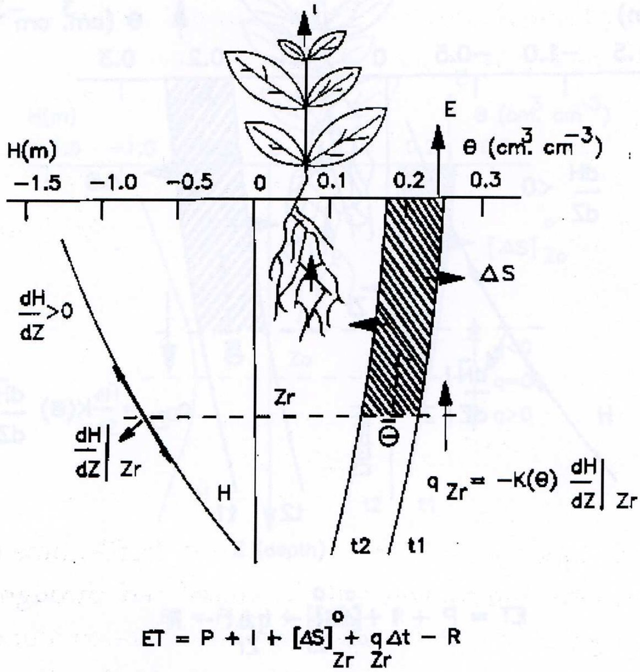

Fig. 4 - Components of water balance equation when contribution of ground water to crop water consumption is significant (i.e., Gc >Gr).

Internal drainage method based on monitoring transient water flux and hydraulic gradient is a field method allowing in-situ measurement of unsaturated hydraulic conductivity. Numerous published work discussing the internal drainage method exist (e.g., Rose et al., 1965; Davidson et al., 1969; Gardner, 1970; Hillel et al., 1972; Nielsen et al., 1973; Wagenet and Addiscot, 1987). It would help to have a better understanding of the method if essential equations are redrived so that questions addressing to the experimental methodology could be handled with expertly confidence.

One dimensional equation describing vertical water flow is

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial Z}\left[K(\theta)\frac{\partial H}{\partial Z}\right] \qquad (9)$$

where H is total soil water hydraulic head (L), Z is depth measured positively downward (L), t is time and other variables are as previously defined. Integration of the equation with respect to soil depth Z yields

$$\int_0^Z \frac{\partial \theta}{\partial t} dZ = \left[K(\theta) \frac{\partial H}{\partial Z} \right]_0^Z \tag{10}$$

In a field test, after saturating surface soil layer within 50 to 60 cm soil depth, if the soil surface is covered with plastic to prevent evaporation and only internal drainage is allowed, soil water flux q at a given depth Z=L is given as

$$q = \frac{d}{dt} \int_0^{Z=L} \theta dt = \left. \frac{dS}{dt} \right|_{Z=L} \cong Z \cdot \left(\frac{d\bar{\theta}}{dt} \right) = \left[K(\theta) \frac{dH}{dZ} \right]_{Z=L} \tag{11}$$

which yields

$$\left. K(\bar{\theta}) \right|_{z=L} = \left[\frac{dS / dt}{dH / dZ} \right]_{z=L,t} \tag{12}$$

During the internal drainage of initially wetted soil profile, time change of soil storage over a given depth (i.e., Z=L) can conveniently be monitored through the use of preferably a neutron moisture gauge. Although hydraulic gradient is often found to be unity (Black et al., 1969; Davidson et al., 1969; Jones and Wagenet, 1984), it can be measured with tensiometers installed at several depths (Fig. 5).

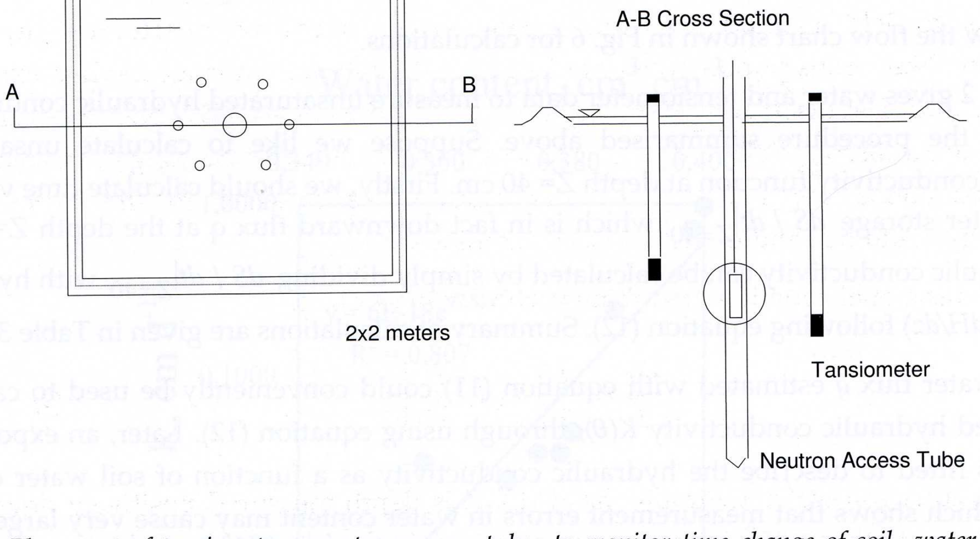

Fig. 5 - Placement of tensiometers, neutron access tube to monitor time change of soil water storage and hydraulic gradient during the internal drainage of initially wetted soil profile.

Field procedure

1. One should set up a basin of approximately 2x2 meters in the experimental field. The levies of about 10 to 15 cm height surrounding the basin can be prepared with soil piled up from the nearby areas. Neutron access tube is installed in the center of the basin. Series of tensiometers are installed at depths of 15, 30, 45, 60 and 75 cm depths with due consideration of whether the soil profile is uniform or layered. Number and depths of installation of tensiometers may be decreased if the experimental soil is uniform. Enough water must be applied to saturate at least 60 to 70 cm of soil. Water can be applied by ponding. Once the ponded water is completely infiltrated, soil surface can be covered with a plastic film to prevent evaporation (i.e., upward flux) and time $t=0$ is recorded as the beginning of drainage when 60 to 70 % of soil surface is free of standing water. During the first two hours of drainage, it is advisable that continuos neutron water gauge (NWG) measurements must be taken to monitor changes of soil water content particularly over the draining zone of the soil profile. Measurement should start from the first depth increment $Z=15$ cm at $t=0$ and proceed to cover the whole draining zone Z_0 as one cycle of measurement. For each measurement soil depth, time (initiation of drainage being at $t=0$) and the neutron counts are recorded. After two hours of continuos measurement, new cycle of measurements starting at depth $Z=15$ cm can start at 30 minutes intervals for the following four hours. Interval of measurements can progressively be increased later on.
2. As for the tensiometers, the readings must recorded at 5 minutes intervals during the first two hours of drainage. The data must include tensiometer number (i.e., depth) and time of measurement. Measurement interval can progressively be increased later on as recommended for the neutron gauge measurements.
3. Follow the flow chart shown in Fig. 6 for calculations.

Table 2 gives water and tensiometer data to measure unsaturated hydraulic conductivity following the procedure summarised above. Suppose we like to calculate unsaturated hydraulic conductivity function at depth Z= 40 cm. Firstly, we should calculate time variance of soil water storage $dS / dt|_{Z=40}$ which is in fact downward flux q at the depth Z=40 cm. Soil hydraulic conductivity can be calculated by simply dividing $dS / dt|_{Z=40}$ with hydraulic gradient (dH/dz) following equation (12). Summary of calculations are given in Table 3.

Soil water flux q estimated with equation (11) could conveniently be used to calculate unsaturated hydraulic conductivity $K(\theta)$, through using equation (12). Later, an exponential curve was fitted to describe the hydraulic conductivity as a function of soil water content (Fig. 7), which shows that measurement errors in water content may cause very large errors in hydraulic conductivity. For example a measurement error in water content of $\pm\Delta\theta = 0.005$

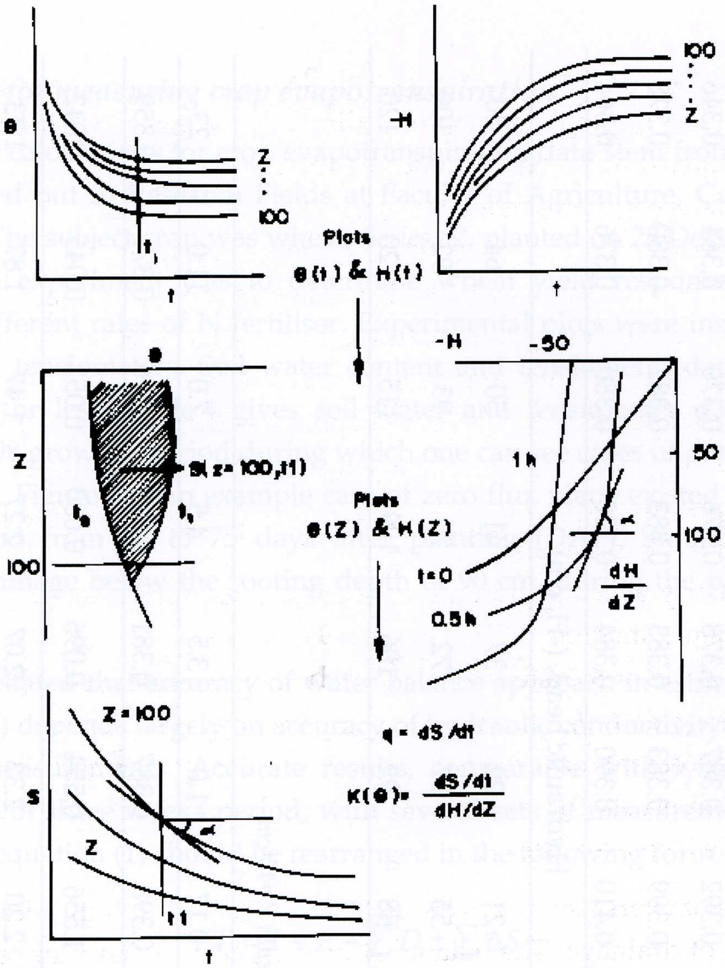

Fig. 6 - Main procedure and calculation steps of field-measured unsaturated hydraulic conductivity.

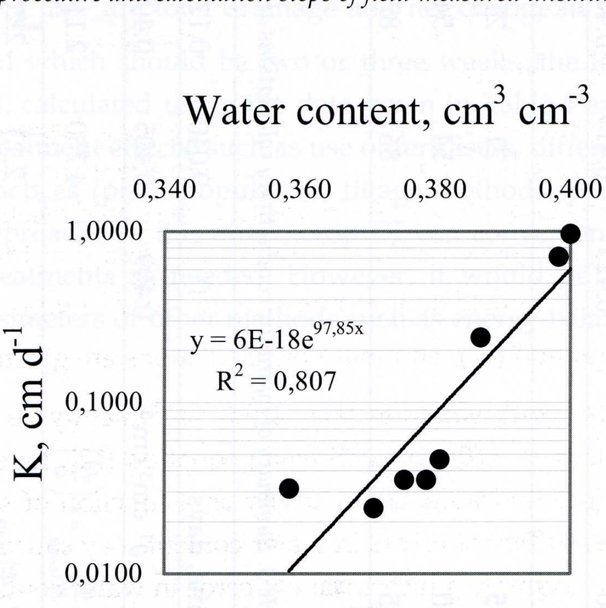

Fig. 7 - Unsaturated hydraulic conductivity function shows strong dependence on soil water content.

***Table 2**. Soil water content (cm3.cm^{-3}) and total hydraulic head (-H, cm) data during field measurement of unsaturated hydraulic conductivity.*

	Time, days									
Depth, (cm)	0	0.040	0.125	0.17	1.0	3.5	4.5	7.0	11.0	23
	Water content, (θ cm^3.cm^{-3})									
20	0.400	0.396	0.393	0.392	0.387	0.378	0.376	0.370	0.364	0.346
30	0.412	0.407	0.401	0.399	0.383	0.383	0.383	0.382	0.380	0.378
40	0.425	0.419	0.413	0.410	0.390	0.384	0.380	0.380	0.376	0.364
	Hydraulic head, (-H, cm)									
15		21	21	21	22	37	41	50	64	80
30		54	54	55	57	72	75	93	92	100
45		86	87	88	92	106	109	115	120	120

***Table 3**. Summary of hydraulic conductivity calculations at soil depth Z=40 cm*

Time, days	0	0.040	0.125	0.17	1.0	3.5	4.5	7.0	11.0	23
$\bar{\theta}^1$ cm^3.cm^{-3}	0.409	0.405	0.400	0.398	0.387	0.381	0.379	0.376	0.371	0.359
$q=\left.\frac{dS}{dt}\right\|_{z=40}=z\cdot\left(\frac{d\bar{\theta}}{dt}\right)$		4.750	2.118	1.556	0.554	0.096	0.080	0.052	0.045	0.042
$dH/dz\|_{z=40}$		2.13	2.20	2.20	2.33	2.07	2.27	1.47	1.87	1.33
$K(\bar{\theta})$, cm.d^{-1}		2.230	0.963	0.707	0.238	0.046	0.035	0.035	0.024	0.31

[1]Average water content calculated over 40 cm of soil profile.

A field example for measuring crop evapotranspiration

The example calculations for crop evapotranspiration data stem from a field experiment which was carried out in Research Fields at Faculty of Agriculture, Çukurova University, Adana, Turkey. The subject crop was wheat, *Series 82*, planted on 28 December 1997. General objectives of the experiment was to determine wheat yield response to supplementary irrigation and different rates of N fertiliser. Experimental plots were installed with neutron access tubes and tensiometers. Soil water content and tensiometer data were collected at weekly intervals or less. Table 4 gives soil water and tensiometer data, covering first 3 months in 1997/98 growing period during which one can see cases of drainage and existence of *zero flux* plane. Figure 8 is an example case of zero flux plane existed at 70 cm soil depth during the period from 68 to 75 days after planting (DAP). Similarly Figure 9 shows occurrence of drainage below the rooting depth of 90 cm, during the period from 45 to 48 DAP.

It should be stated that accuracy of water balance approach in estimation of crop water consumption (ET) depends largely on accuracy of hydraulic conductivity function and of soil water content measurements. Accurate results, comparable with lysimeter data, can be achieved for two or three weeks period, with several sets of measurement in between. For this purpose the equation (1) should be rearranged in the following form.

$$ET = I + P - \sum D \pm \sum \Delta S \qquad (13)$$

where $\sum D$ and $\sum \Delta S$ are total drainage and net change in soil water storage during the calculation period which should be two or three weeks, the least. Cumulative ET and the drainage loss (D), calculated using the data given in Table 4 are shown in Fig. 10. One can easily evaluate treatment effects, such as use of fertilisers, different crop varieties, differences in agronomic practices (plant population, tillage methods, planting date etc.), on ET with water balance approach. To this effect, crop ET can conveniently be calculated in as many replicates and treatments as needed. However, it would be an unimaginable venture to attempt to use lysimeters or other methods such as energy balance approach and the like, in the same context.

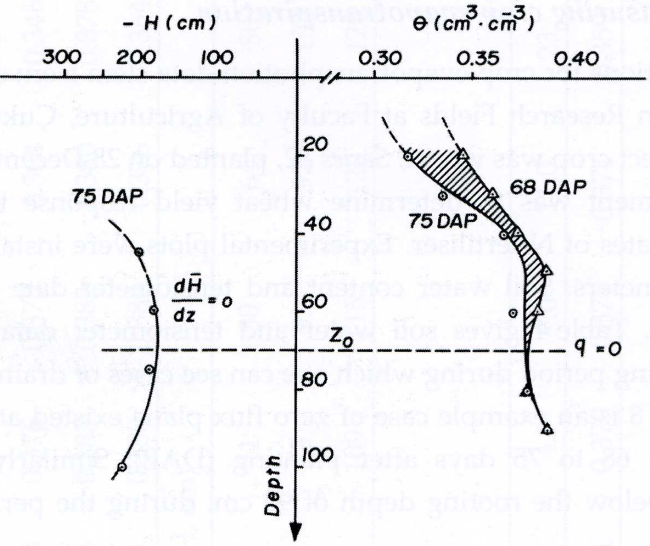

Fig. 8 - Existence of zero flux plane at 70 soil depth during the growing period from 68 to 75 days after planting.

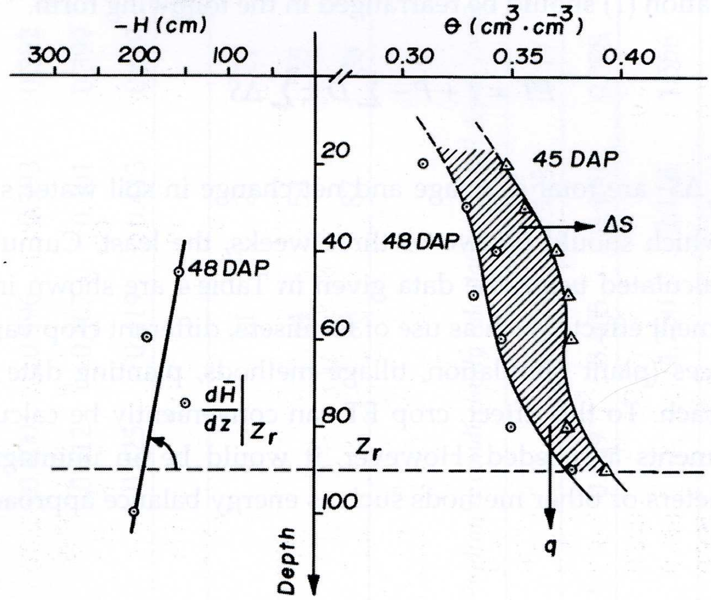

Fig. 9 - Soil water and total hydraulic head distribution profiles under a case where drainage takes place.

Table 4 *- Soil water and tensiometer data to estimate crop water consumption (ET)*

Depth	Date/Days after planting (DAP)								
	6/2/98	13/2/98	16/2/98	20/2/98	27/2/98	2/3/98	6/3/98	13/3/98	20/3/98
(cm)	38	45	48	52	59	64	68	75	82
	Water content, ($cm^3 \cdot cm^{-3}$)								
20	0.334	0.348	0.310	0.324	0.304	0.298	0.346	0.317	0.365
30	0.348	0.356	0.331	0.353	0.339	0.335	0.361	0.335	0.402
40	0.348	0.370	0.344	0.381	0.361	0.364	0.374	0.367	0.402
50	0.331	0.376	0.333	0.387	0.379	0.379	0.389	0.389	0.409
60	0.352	0.378	0.346	0.387	0.381	0.389	0.385	0.372	0.380
80	0.357	0.376	0.351	0.376	0.386	0.379	0.380	0.378	0.380
90	0.371	0.394	0.379	0.395	0.405	0.396	0.390	0.390	0.390
	Total hydraulic head, -H (cm)								
45	149	169	156	188	231	261	129	221	83
60	156	184	194	176	191	219	162	184	126
75	176	223	147	199	207	220	183	193	108
100	190	219	206	196	206	240	191	234	143
$Z\|_{q=0}$				75	90	80	80	70	
$dH / dz\|_{Z=90}$	-0.850	-0.889	-0.889						-1.111
S_i, (mm)	312	331	301	270	326	278	295	244	346
S_{i-1}, (mm)	370	312	331	272	327	287	278	257	320
$\pm\Delta S$ (mm)	-58	19	-30	-2	-1	-9	17	-13	26
P/I, mm	88.5	1			11	11		10	50
$\theta\|_{Z=90}$	0.371	0.394	0.379						0.390
$q\|_{Z=90}$ ($cm.d^{-1}$), Eq. 3	0.03	0.295							0.250
D (mm), Eq. 4	2	18	4						15
Δt (days)[1]	6	6	6						6
$\sum ET$ (mm)		108.5				168.5			183.5

[1] Time interval in equation (4) used to calculate D is assumed to be the measurement interval, 6 days.

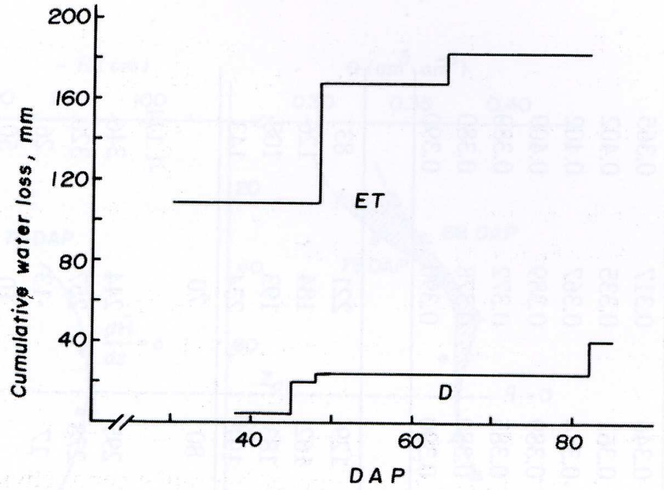

Fig. 10 - Cumulative water loss from plant rooting depth of 90 cm under wheat during early period of 1997/98 growing season.

CONCLUSIONS

One can conveniently study and evaluate various factors affecting plant water consumption through using water balance approach. For example effects of fertiliser application, plant variety, tillage and of agronomic practices (e.g., plant population, tillage methods, planting date etc.) on plant water consumption can easily be investigated in field conditions. One can include as many treatments and replicates as needed in the experimental work where direct ET measurements can be made separately and independently in each field plot. However, one can not carry out similar scale of studies with lysimeters. High cost of lysimeters become a major constraint to construction of lysimeters in equal number of treatments and replicates. The best one can do is to include only one treatment if the lysimeter is to be used, and no statistical analysis can be carried out although some low cost drainage type lysimeters can be constructed in adequate numbers to accommodate several treatments or replicates. An other disadvantage of lysimeters is the fact that they rarely contain undisturbed soil which may not reflect the true behaviour of field soil profile.

Agrometeorological methods used to estimate ET require large fields to meet environmental boundary conditions; whereas, water balance approach can be applied even in small field plots. However, it should be pointed out that ET measurements, with agrometeorological methods, can be carried out for short periods as small as even one minute; whereas the measurements describing periods shorter than one week may be erroneous in ET estimates made with water balance approach. Thus the best methodology depends on one's objectives and institutional facilities available to implement field experiments on ET measurements.

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