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IN SITU ESTIMATION OF ACTUAL EVAPOTRANSPIRATION. A CASE STUDY IN ARGOS PLAIN

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Abstract

The following work refers to an experimental methodology employed for in situ monitoring of specific soil water fluxes constituting water balance components. The test area is located in the plain of Argos – Greece, within an orange grove. A micrometeorological station was installed in the site, equipped with several sensors for real time monitoring of various atmospheric parameters as well as water content and temperature in the soil profile. The soil profile was made accessible for sampling through a rectangular pit which was excavated close to the station. The soil water content was monitored making use of TDR sensors which were calibrated against the traditional neutron probe technique and also by soil sampling. Tensiometeres were also installed in four different depths for monitoring the matrix potential. A software programme was developed for the analysis and the evaluation of the data collected in a 10 - minute time step. The analysis of the data showed that the three - year average of Actual Evapotranspiration, in this irrigated field, was approximately 857 mm, out of which almost 600mm occur between April and September and 260 mm in the winter period. Those results show that there is no significant water surplus for deep infiltration and aquifer recharge in clayey and clay - loam soils in this region.

Key words: *Actual Evapotranspiration, Recharge, water balance, TDR, Argolid.*

Περίληψη

Η παρούσα εργασία αναφέρεται σε μια πειραματική μεθοδολογία η οποία εφαρμόστηκε για την επιτόπου καταγραφή συνιστωσών του υδατικού ισοζυγίου σε εδαφική κατατομή. Το σχετικό πείραμα εφαρμόστηκε σε καλλιέργεια εσπεριδοειδών στην περιοχή του Αργολικού πεδίου. Στην περιοχή εγκαταστάθηκε ένας μικρομετεωρολογικός σταθμός εξοπλισμένος με διάφορα όργανα καταγραφής διαφόρων ατμοσφαιρικών παραμέτρων, εδαφικής υγρασίας και θερμοκρασίας σε πραγματικό χρόνο. Η πρόσβαση στο εδαφικό προφίλ επιτεύχθηκε με την ανόρυξη ενός ορθογώνιου ορύγματος πλησίον του μετεωρολογικού ιστού. Η καταγραφή της εδαφικής υγρασίας σε πραγματικό χρόνο έγινε με τη χρήση κατάλληλων αισθητήρων η λειτουργία των οποίων βασίστηκε στη μέθοδο "TDR". Οι αισθητήρες αυτοί βαθμονομήθηκαν με τη χρήση της κλασικής μεθόδου των νετρονίων καθώς επίσης και με τη λήψη εδαφικών δειγμάτων από αντίστοιχα βάθη της εδαφικής κατατομής. Επίσης πλησίον του ορύγματος εγκαταστάθηκαν τέσσερα τασίμετρα για την μέτρηση του υδραυλικού φορτίου στην ακόρεστη ζώνη. Η επεξεργασία των καταγραφών,

δεκάλεπτου χρονικού βήματος, πραγματοποιήθηκε με τη χρήση ενός κατάλληλου λογισμικού το οποίο αναπτύχθηκε για τις ανάγκες της συγκεκριμένης έρευνας. Η επεξεργασία δεδομένων τριών ετών έδειξε ότι η συνολική ετήσια πραγματική εξατμισοδιαπνοή στη συγκεκριμένη αρδευόμενη καλλιέργεια ήταν 857 mm από τα οποία τα 600mm περίπου λαμβάνουν χώρα μεταξύ Απριλίου και Σεπτεμβρίου και τα 260 κατά τη χειμερινή περίοδο. Τέλος, προέκυψε ότι δεν υπάρχει σημαντικό πλεόνασμα νερού για βαθιά διήθηση σε αργιλώδη και αργιλοπηλώδη εδάφη στην περιοχή.
Λέξεις κλειδιά: *Πραγματική εξατμισοδιαπνοή, Κατείσδυση, υδατικό ισοζύγιο, Αργολίδα.*

1. Introduction

The objective of water balance estimation in aquifers and aquifer systems is their spatiotemporal estimation of inflows and outflows. The major sources of aquifer inflows or replenishment, usually referred to as "recharge", include deep infiltrated rain water, loosing stream seepage, various lateral inflows from surrounding aquifers, irrigation returns, water main and canal losses etc. Outflows include, the various pumping abstractions, from aquifers undergoing any kind of exploitation either through artificial means or even to natural outflows such as springs, gaining streams and sea, and also as lateral outflows to surrounding aquifer according to the prevailing hydrodynamic conditions.

The sound estimation of direct groundwater recharge, which is the water surplus of rain and irrigation water, in unconfined aquifers, is probably the most important water balance component, since it used not only in the estimation of the renewable water resources in aquifers but also assists in the elucidation of their working mechanisms thus, contributing to their rational water use and management. This issue continues to attract the interest of the scientific community worldwide, not only in the field of groundwater hydrogeology but also in other fields of hydrology such as soil hydrology and physics and surface hydrology as well (Lerner *et al.* 1990, UNEP 2002, Scanlon *et al.* 2002 e.t.c.).

The recharge or "*water surplus*" is estimated as a difference between inflows (precipitation and irrigation) and the sum of various outflows including actual evapotranspiration and runoff allowing also for the changes of moisture in the soil profile. Hence, the process of aquifer recharge estimation is usually performed through the estimation of the water fluxes in the soil profile.

The most common methods of water balance estimation incorporate direct *in situ* measurements, rainfall – runoff models, Darcian methods, tracer techniques etc. The direct *in situ* measurements include instruments like lysimeters, and methodologies based on local field measurements such as neutron probes techniques and Time Domain Reflectometer (TDR) devices.

The following refers to an experimental work designed for estimating the soil water fluxes of a soil profile in an orange grove in the plain of Argos - Greece. The ultimate purpose of this experiment was the estimation of the actual water needs of this prevailing crop in the selected irrigated area. The soil moisture data collected from the *in situ* monitoring TDR devices were calibrated against neutron probe measurements and soil samples.

2. Experimental procedure - methodology

The experimental instrumentation described below, was installed within an orange grove situated in the plain of Argos - Greece. Since this crop is the most prevalent in the region, one of the study objectives was the estimation of its actual water needs that is closely relevant to the Actual Evapotranspiration. This parameter is a fundamental component of the aquifers' water balance estimation.

Thus, various sensors were installed within an orange grove for monitoring atmospheric parameters as well sensors within a pit excavated close to the sensors' mast, in order to monitor soil water content, temperature and soil heat flux. The detailed structure of the "station" is presented in Figure 1. The instruments were installed according to following structure:

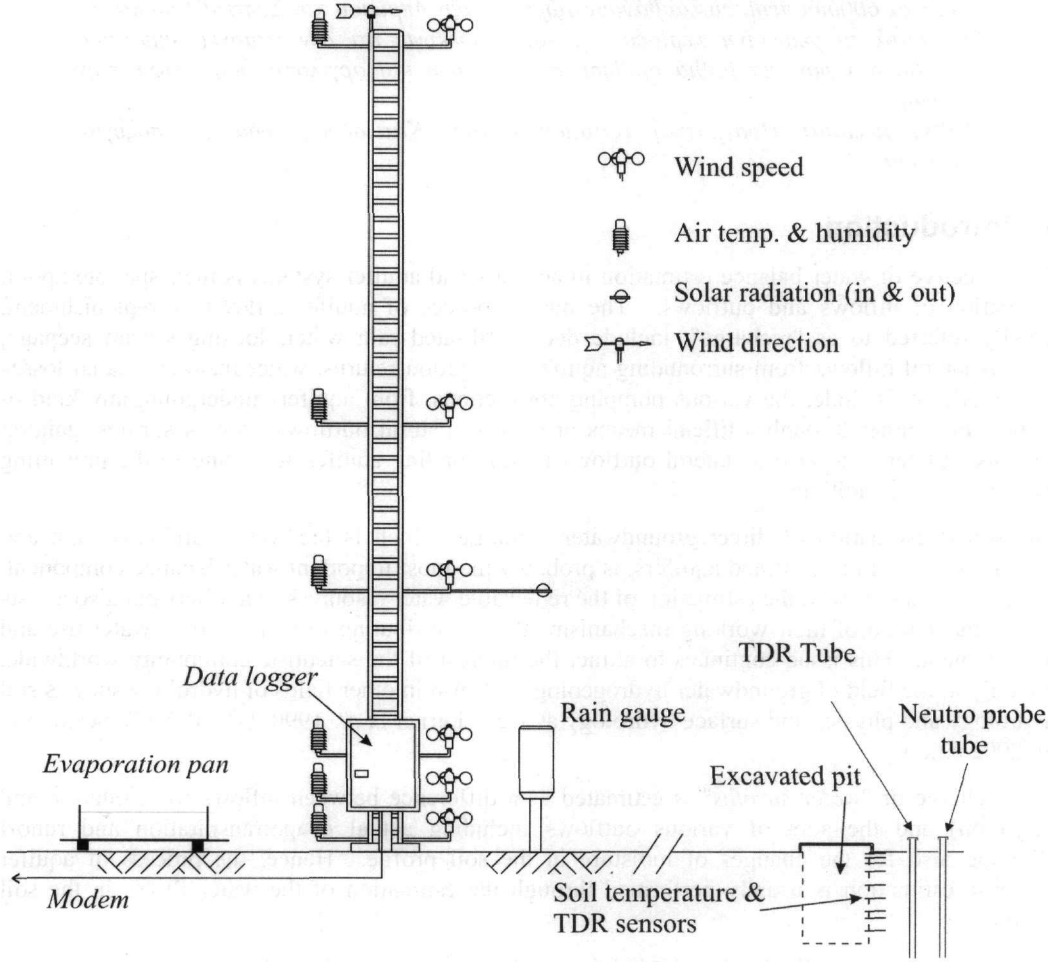


Figure 1 - Detailed structure of the micro-meteorological station and the excavated pit

- ***On the micro-meteorological mast:***
  - At six different elevations from the ground (0.5, 1, 2, 5, 8 and 15 m) air temperature, air humidity and wind speed sensors.
  - On the top of the mast, at an elevation of 15 meters a wind direction sensor was installed
  - Above the canopy level, at elevation of 5 meters solar radiation sensor equipped with incoming and outgoing radiometers and pyranometers
  - A rain gauge
  - A "*Class A*" evaporation pan.
  - A Data logger which was programmed to save all the above parameters at 10 min time step.

- ***Within the excavated pit:***
  - Nine TDR (Time Domain Reflectometers) sensors for monitoring the water content in the soil profile at depths of 2.5, 10, 20, 35, 60, 84, 107, 120 and 142 cm from the ground surface.
  - Seven soil temperature sensors at depths of 2.5, 5, 10, 20, 50, 70 and 100 cm from the ground surface.
  - Two *heat-flux plates* at depths of 0.5 and 5 cm.

Also, close to the pit two pipes were installed vertically for neutron probe measurements and measurements with another extra TDR device. The neutron probe method was employed as a classical standard method for testing and comparing the corresponding TDR records.

The soil suction head as well as the vertical hydraulic gradients were monitored on a daily basis by using four tensiometers installed close to the excavated pit in different depths namely at 20, 45, 75 and 115 cm from the soil surface.

3. Application of methodology and Results

3.1. Monitoring of soil moisture

Soil moisture can be measured or monitored by various methods either in the lab or in the filed. One of the most widely used is the neutron probe method while other modern ones such as the "*Time Domain Reflectometer*" method have been recently invented. The latter, by making use of specialized equipment, enables the continuous and *in situ* monitoring of soil water content. It also does not involve any danger as the traditional neutron probe method which incorporates a radioactive source. Throughout this experiment, soil water content was primarily monitored by using the TDR sensors. The various measurements were recorded with a data logger installed on the nearby micrometeorological mast. Also, in regular time intervals neutron probe measurements were conducted and additionally, soil samples were taken from the pit profile to the lab for testing their water content, in order to calibrate and validate the various measurements from all the above devices.

A first step of processing the large amount of monitored data was a reliability check in order to find any unusual or extraordinary values and other possible errors. These mainly concerned the range of the recorded soil water values as well as the other pertinent parameters.

Neutron probe measurements were carried out by using a portable equipment[1] at seven different depths (20, 40, 60 ,80 , 100, 120 and 140 cm from the soil surface).

The TDR sensors selected to monitor in situ the water content of the soil profile were the "CS615" sensors manufactured by "Campbell Scientific^{TM}" (1996). They are made of two parallel rods, 3.2 mm thick, 300 mm long and 32mm apart. During measurements, an electrical pulse is transmitted and travels along the rods which reflects to their ends and returns back to the transceiver. The total travel time of the emitted pulse depends on the dielectric constant of the surrounding material. The dielectric constant in turn depends largely on soil water content. The sensor then, outputs on the data logger a square wave of ±2,5V DC aperture whose period (τ) depends of the soil water content (θ). The accuracy of this method is usually of the order of ±2%. The sensors are supplied by the manufacturer with a pre-selected formula for converting the pulse period (τ) to soil water content (θ) which is:

$$\theta(\tau) = A\tau^2 + B\tau + C \tag{1}$$

[1] "*TROXLER^{TM}" (model 4300)*, with radioactive source *Am-241-Be*.

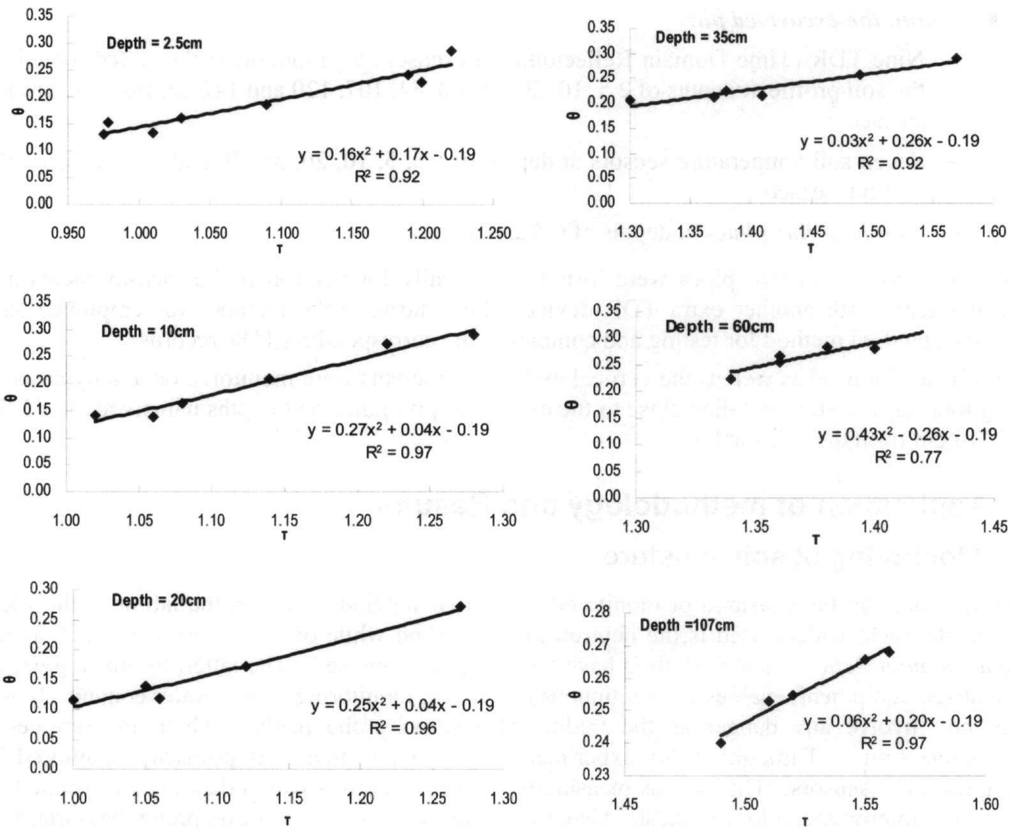


Figure 2 - Examples of TDR – sensors' calibration

The original coefficients A, B and C of the above equation are respectively 0.335, 0.037 and 187. They represent average soil characteristics and their values depend both on the mechanical structure of the soil and also on the conductivity of the soil water.

As it was found from the first field records, the above selected coefficients yielded erroneous results of soil water content which deviated significantly from the corresponding values produced by both the neutron probe and the soil sampling. Thus, new coefficients were calculated by taking soil samples at various water contents, from the corresponding measuring depths in the excavated pit and correlated these with the wave periods (τ) recorded by the TDR sensors (Fig. 2).

On Figure 3 soil water profiles recorded with the calibrated coefficients of Equation 1 are shown together with the profiles produced from soil samples and the neutron probe. This comparison shows that the profiles produced with the three different methods do not vary significantly.

An additional validation test was the operation of the sensors on the extreme dry and wet condition of the soil profile. Figure 4 shows soil water profiles produced with neutron probe and soil sampling at the very dry period of the year in the summer, just before the irrigation of the farm, as well as the same profiles immediately after the end of the irrigation event and a complete flooding of the soil surface. Profile I, corresponds to the minimum soil moistures recorded while profile II, to the maximum moistures attained.

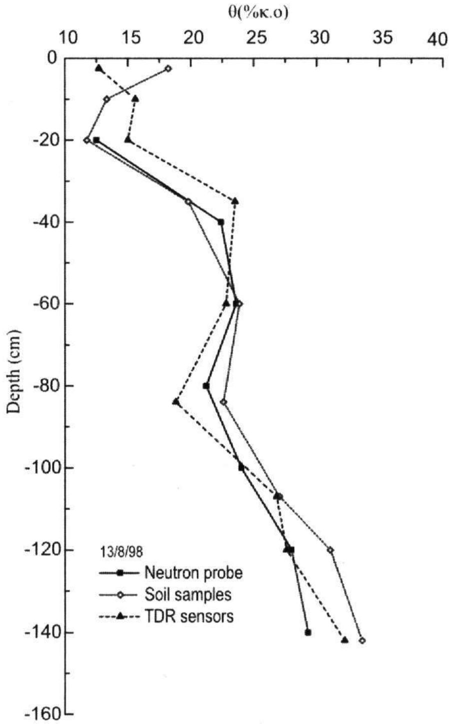


Figure 3 - Comparison of soil moisture profiles as recorded by three different methods

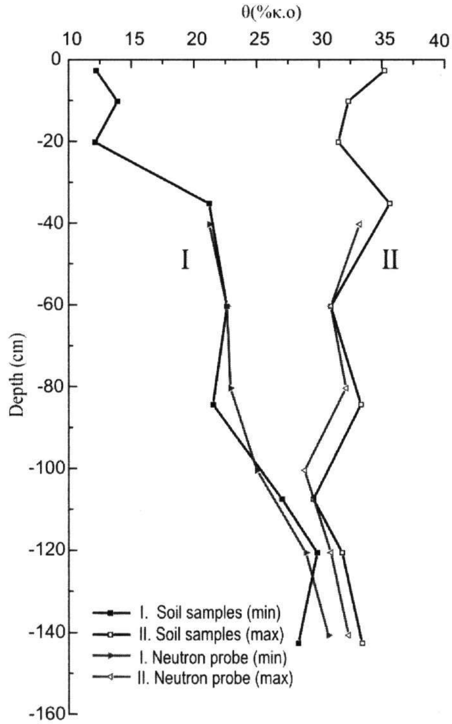


Figure 4 - Soil moisture profiles close to the minimum and maximum water contents

3.2. Data analysis and results

The processing and evaluation of the large amount of collected data, recorded in such small time intervals was performed by developing computer software specifically designed for the needs of this study. Hence, it was considered that this software should be able to assist in carrying out the following tasks:

- *to be able to graphically design, on the computer screen the parameter profiles recorded, in every time step (dynamically) in order to identify any gaps, outliers and recording errors.*
- *to calculate several theoretical and experimental water balance components which are produced either from the pertinent equations or from the processing of recorded soil moisture data.*
- *to save selected calculation in data files for further processing*

Figure 5 shows an example of atmospheric and soil parameter profiles as well as other data recorded from the various sensors of the micro-meteorological station which are plotted by using the above software[2]. This computer program is able to plot dynamically profiles of atmospheric parameters such as the wind speed (m/sec), the air temperature (^{0}C), the relative humidity (%) and also calculates the cumulative wind direction rose diagram. On the second row of plots, profiles of soil temperature and water content follow.

[2] Unpublished software written in *C++*

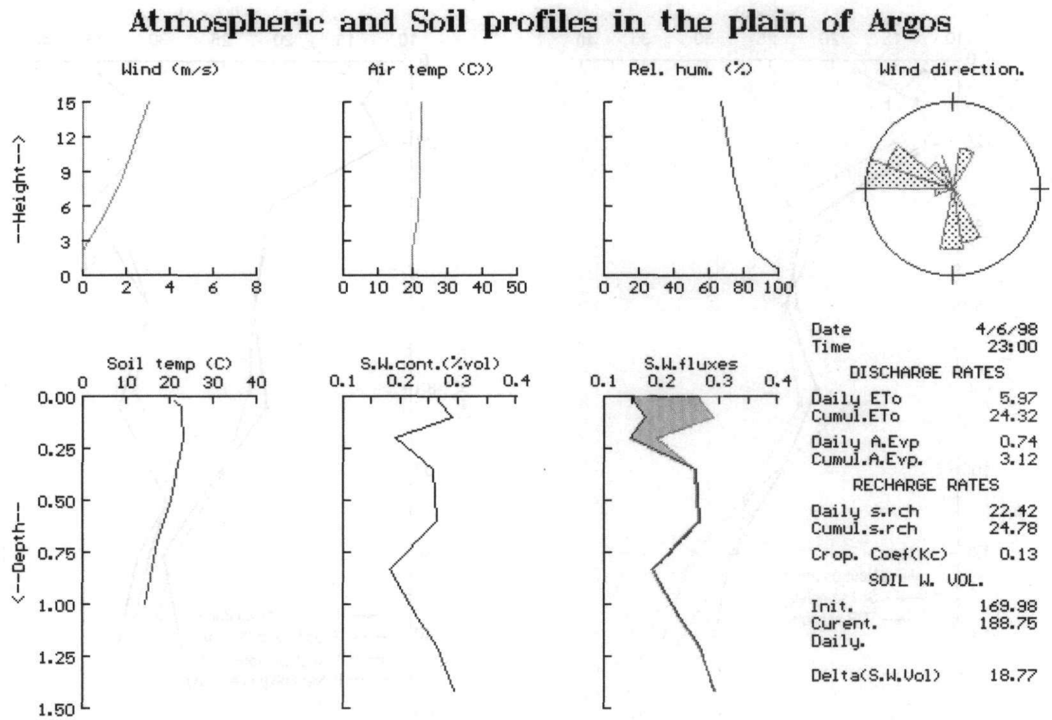


Figure 5 -A screen dump of the software developed for the processing of the data recorded

The third plot, on the bottom row, shows the change of soil water volume which is calculated as the soil moisture difference between two consecutive time steps. This difference is recorded on a daily time step and approximates either the daily recharge (rain or irrigation) or discharge (actual evapotranspiration or deep infiltration) flux.

In addition to the above plots, on the lower right part of the screen, calculations of various soil water balance components follow, which are classified in two different categories namely, "recharge rates" and "discharge rates".

The water balance components and the various parameters calculated on the lower-right part of the screen (Fig. 5) are the following:

- ***Discharge Rates:***
  - ***Daily ET_0:*** Daily reference potential evapotranspiration (mm). Is calculated cumulatively from the hourly values by making use the *"FAO Penman - Monteith"* equation. However, it has to be stressed that this equation has been developed for grass and does not completely represent the orange crop environment.
  - ***Cumul. ET_0:*** The cumulative reference potential evapotranspiration (mm). Is calculated from the corresponding daily values *(Daily ET_0)* for the entire calculation period.
  - ***Daily A. Evp.:*** The actual daily water losses (mm) from the soil profile which, are calculated from consecutive daily soil water profiles. This integration is calculated from the soil surface to the depth of 80cm where recordable changes of soil water content are observed.
  - ***Cumul. A. Evp.:*** The cumulative actual water losses (mm) from the soil profile. They're calculated from the corresponding daily values (Daily A. Evp) for the whole calculation period which is usually monthly.

- ***Recharge Rates:***
  - ***Daily s. rch.:*** They concern the water inflows (mm) in the soil profiles and are also calculated, as in the above case, from the daily consecutive profiles. The integration is also done from the soil surface to the depth of 80cm. Thus, the daily *discharge* or *recharge* flux (*f*), is calculated according to the following integral:

$$f = \int_{z_1}^{z_2} swc \, dz$$

and it was numerically implemented as

$$f = \sum_{i=0}^{i=80} swc_i$$

where,

z_1 the soil surface elevation (depth =0)

z_2 the depth of 80 cm

swc the Soil Water Content as calculated by linear interpolation between monitoring points[3]

  - ***Cumul. s. rch.:*** The cumulative actual daily inflows in the soil profile. They are calculated from corresponding daily values (Daily s. rch) for the entire period of calculations.

- ***Soil Water Volume:***
  - ***Init.:*** The initial soil water volume (mm) in the soil profile from the soil surface to the depth of 80cm. It is calculated only in the beginning of the simulation.
  - ***Current.:*** The current water volume (mm) in the soil profile. Is calculated in every time step
  - ***Delta (S.W.Vol):*** The difference between the starting soil water volume and the final one. Is calculated in the end of program run in order to be used together with the other fluxes for the estimation of the entire soil water balance.

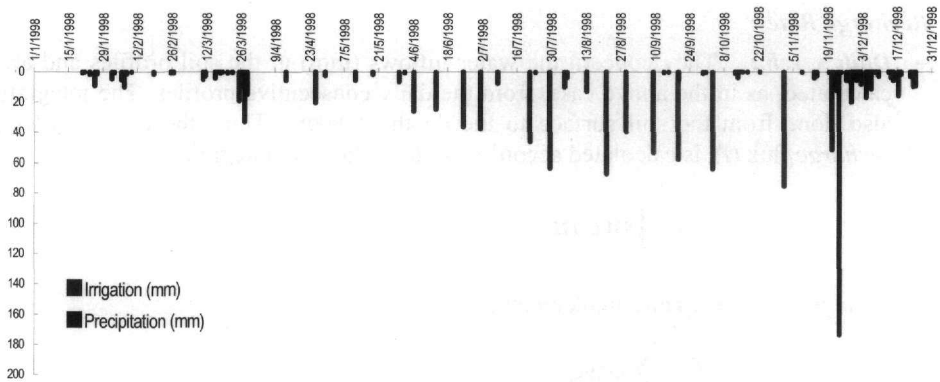
The soil water profiles show that moisture changes under the depth of 80cm are negligible and range within the measurement error of the method (±2 %). The increased content of coarse materials within the depth of 50–107 cm is responsible for a higher hydraulic conductivity zone which is reflected by the relatively smaller ranges of moisture changes.

As it was mentioned before, the water balance was estimated from the daily changes of the soil moisture profile. The water loses from the profile are not attributed entirely to the actual evapotranspiration but, a small portion seeps to deeper horizons, mainly after heavy and prolonged rainfall or irrigation events.

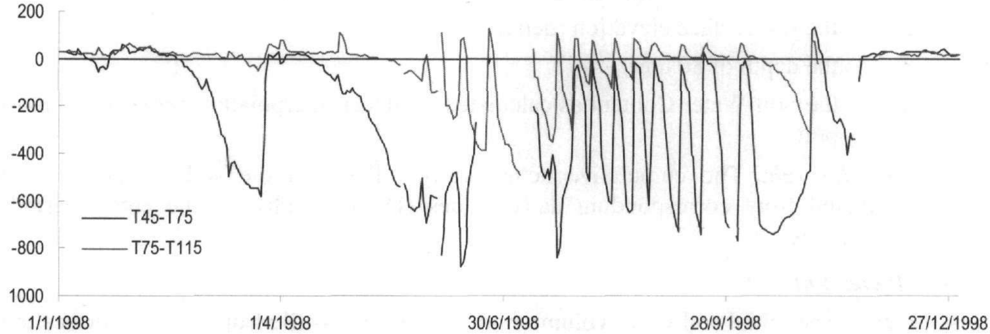
It is generally accepted that deep infiltration can happen only when the soil moisture content exceeds the field capacity of the soil or alternatively when downward hydraulic gradient develops.

Figure 6b shows the changes of hydraulic gradients between two different depths (45-75 cm and 75-115 cm) together with the corresponding rainfall and irrigation events (Fig. 6a). On the same graph also the calculated soil moisture losses due to actual evapotranspiration are presented. The seasonal fluctuation of the above hydraulic gradients as shown on Figure 6b lead to the following conclusions:

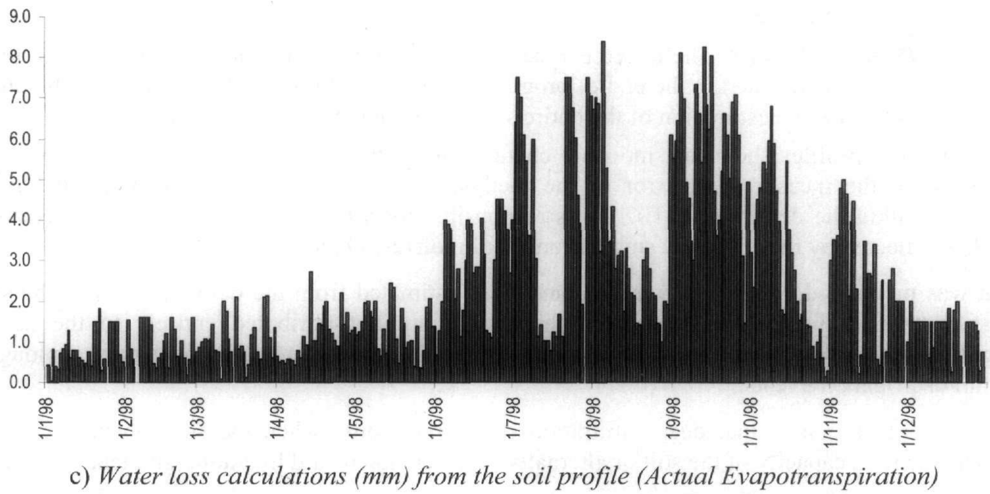
[3] A later version of the software, running on MS-Windows environment, uses interpolation on cardinal splines



a) *Daily depths of rainfall and irrigation events (mm)*



b) *Fluctuations of hydraulic head gradients (cm of water) in different depths.*



c) *Water loss calculations (mm) from the soil profile (Actual Evapotranspiration)*

Figure 6 -Various features of the soil water fluxes as calculated for the year 1998

– The period from *November 10th to February 20th*: Relatively positive[4] (downward) hydraulic gradients without remarkable changes prevail. This period, the water loss from the soil due to

[4] Conventionally, hydraulic gradients from the soil surface\ downwards to deeper horizons are considered as positive.

evapotranspiration is minimum and the soil is mostly at field capacity[5]. Thus, any additional water input either from the rainfall or from the frost-prevention irrigation, constitute a water surplus that mostly becomes deep infiltration.

- The period from *February 20th to November 10th:* As Spring arrives, approximately on February 20th, negative hydraulic gradients (from the deeper to the shallow horizons) start developing which shows clearly orange "trees wake up" and start absorbing water from the soil contributing to the mechanism of (actual) evapotranspiration. Those water losses are met during the early spring months first by depletion soil moisture storage and then by sparse rainfall events or irrigation.

  During all this period the hydraulic head gradients as monitored by tensiometers T45 and T75, are always negative which shows that soil water moves upward, from the depth of 75cm to 45cm that is consumed entirely for evapotranspiration. While the deeper hydraulic gradients (75-155 cm) are mostly negative, some periods are identified where small negative gradients are followed by positive ones. Hence, it could be assumed that small potential downward water movements are counterbalanced by upwards water movements and no remarkable downward water movements occur.

On the other hand, in the first case (10/10-20/2) positive gradients prevail on the profile which means that a water surplus is available that could potentially become aquifer recharge in unconfined zones.

The pressure head (*H*) of the profile was monitored on a daily basis making use of tensiometers[6] (Fig. 6b). Furthermore, the hydraulic head was calculated as the sum of the pressure head (*H*).

From the elaboration of the collected data, a daily time series of the actual water losses from the upper zone of the soil profile were produced which approximates the actual evapotranspiration for this specific cultivation of orange trees (Fig. 6c).

It has to be noted that during the winter period, some outlier values were monitored due to the temporal soil flooding followed by immediate seepage, after heavy storm. In this case an evaporation threshold was set in the calculation which was estimated from the evaporation values during the following days.

Table 1 shows the average actual evapotranspiration as calculated for three different years namely, 1997, 1998 and 1999 with the above procedure while in Figure 7 those estimates are shown together with the corresponding monthly rainfalls.

Figure 7 shows that from November to March, actual evapotranspiration is lower that precipitation thus. Hence, a water surplus develops which could contribute to deep infiltration and aquifer recharge and also to surface runoff. Between March and October a soil moisture deficit appears that is supplemented by irrigation. The total actual evapotranspiration which occurs between April and October is approximately 600-650 mm. On the basis of the total actual evapotranspiration calculated with the above methodology, the water surplus for this region from 1964 to 1997 was calculated (Fig. 8). This surplus was calculated as the difference between each monthly rainfall and the corresponding average monthly actual evapotranspiration.

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[5] The field *specific capacity (% per volume)* of this specific soil profile was found to be of 28 % while laboratory measurements of disturbed soil samples gave values of 40 % (Giannoulopoulos 2000).

[6] The mercury tensiometer readings were transformed to actual hydraulic heads by allowing for the geometrical features of the installations (Poulovassilis 1986).

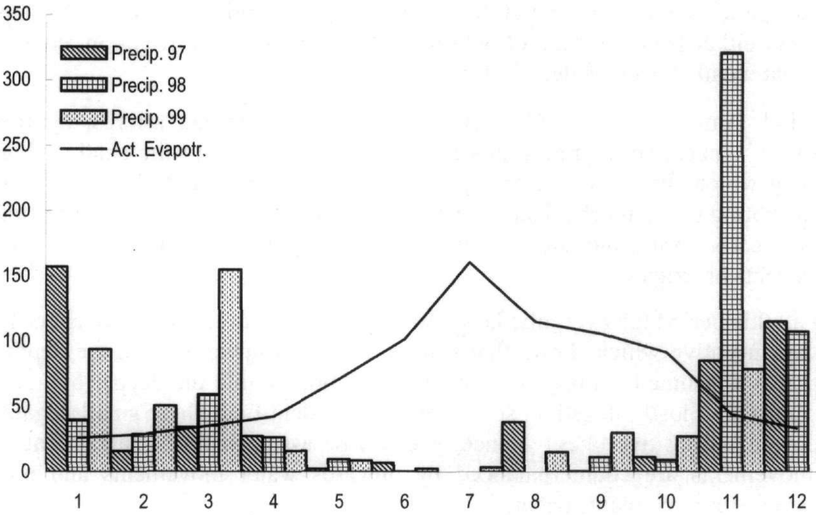

Figure 7 -Average actual evapotranspiration as calculated for three consecutive years, 1997, 1998 and 1999 together with the corresponding monthly rainfalls

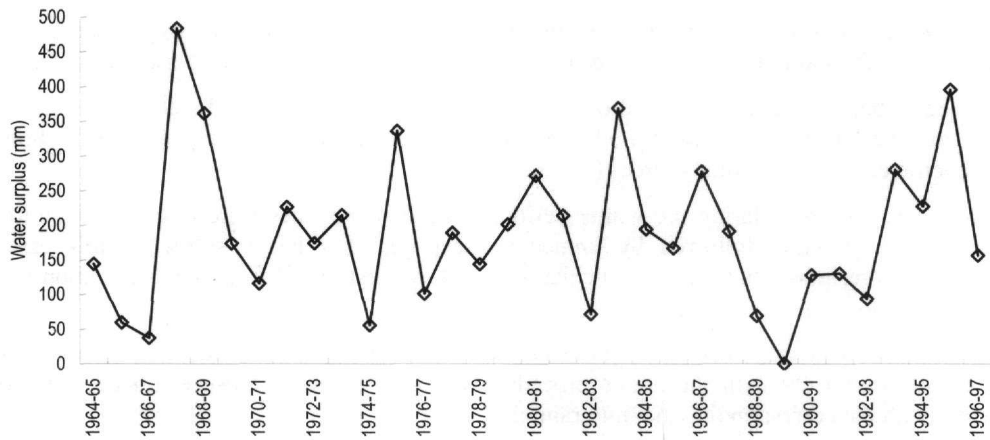

Figure 8 - Annual water surplus calculated from the above estimates of actual evapotranspiration.

Table 1 - Average monthly values of Actual Evapotranspiration calculated from the elaboration of recorded time series of soil moisture profiles

Month	J	F	M	A	M	J	J	A	S	O	N	D
Act. Evap/tion (mm)	26	29	35	43	71	102	161	115	106	92	44	33

This water volume does not entirely reach the underlying aquifers since part of it, mainly after heavy rains becomes surface runoff. It is generally assumed that surface runoff to start rain intensity should by higher than the final seepage water velocity of the soil. Those seepage velocities have been measured in various soil profiles by and found to range between 1,5 and 17,8 cm/h (Giasoglou *et al.* 1983, Giannoulopoulos 2000) while in the above case is estimated that do not exceed 2,5 cm/h. Since the available data show that rain intensity from 1964 to date rarely exceeded the above velocity threshold of 2,5 cm/h it can be envisaged that surface runoff, at least at the surround part of the plain is negligible. On the contrary, water surplus and surface runoff occurs at the central and southern part of the plain where clayey soils and confined aquifers prevail thus, the operation of an efficient drainage network is deemed necessary.

4. Acknowledgments

The authors express their sincere thanks to the owners of the experimental farm situated close to Argos (Koutsopodi), *N. & D. Spanos*, for their plentiful assistance and patience at all stages of construction and operation of the experimental station.

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