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WATER BALANCE AT THE LAND-WATER-ATMOSPHERE CONTINUUM

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WATER BALANCE AT THE LAND-WATER-ATMOSPHERE CONTINUUM

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1. Introduction

Soil water relations in the Land-Water-Atmosphere continuum are very important to be known for any agro-ecosystem. Water cycling in a watershed or in a cropped field can be characterized and quantified by water balances, which are the computation of all water fluxes at the boundaries of the system under consideration. It is an itemized statement of all gains, losses and changes of water storage within a specified elementary volume of soil. Its knowledge is of extreme importance for the correct water management of natural and agro-systems. Gives an indication of the strength of each component, which is important for their control and to ensure the utmost productivity with a minimum interference on the environment.

Let us make a panoramic overview of the SOIL-PLANT-ATMOSPHERE system in relation to agricultural production. The atmosphere rests over the soil and the plant connects both, growing upwards (shoot) and downwards (root). Our interest lies in the plant, more specifically in its yield, which is a function of the available energy coming from the Sun, the climate, the soil, crop management, genotype, … (Figure 1). The fundamental equation for crop yield is based on the photosynthesis process, by which carbon dioxide from the atmosphere and water from the soil are combined to produce sugar inside chloroplasts of green plants, using solar energy:

$$\frac{1M\ CO_2}{atmosphere}+\frac{1M\ H_2O}{soil}+\frac{E}{atmosphere} \quad \rightarrow \quad \frac{1M\ CH_2O}{yield}+\frac{1M\ O_2}{atmosphere}$$

The energy source E is the Sun, accounted as global radiation GR, available for the photosynthetic process as net-radiation NR. This energy E defines the air temperature T_{air} and together with the rainfall R and the evapotranspiration ET, the prevailing CLIMATE which controls crop production, is defined.

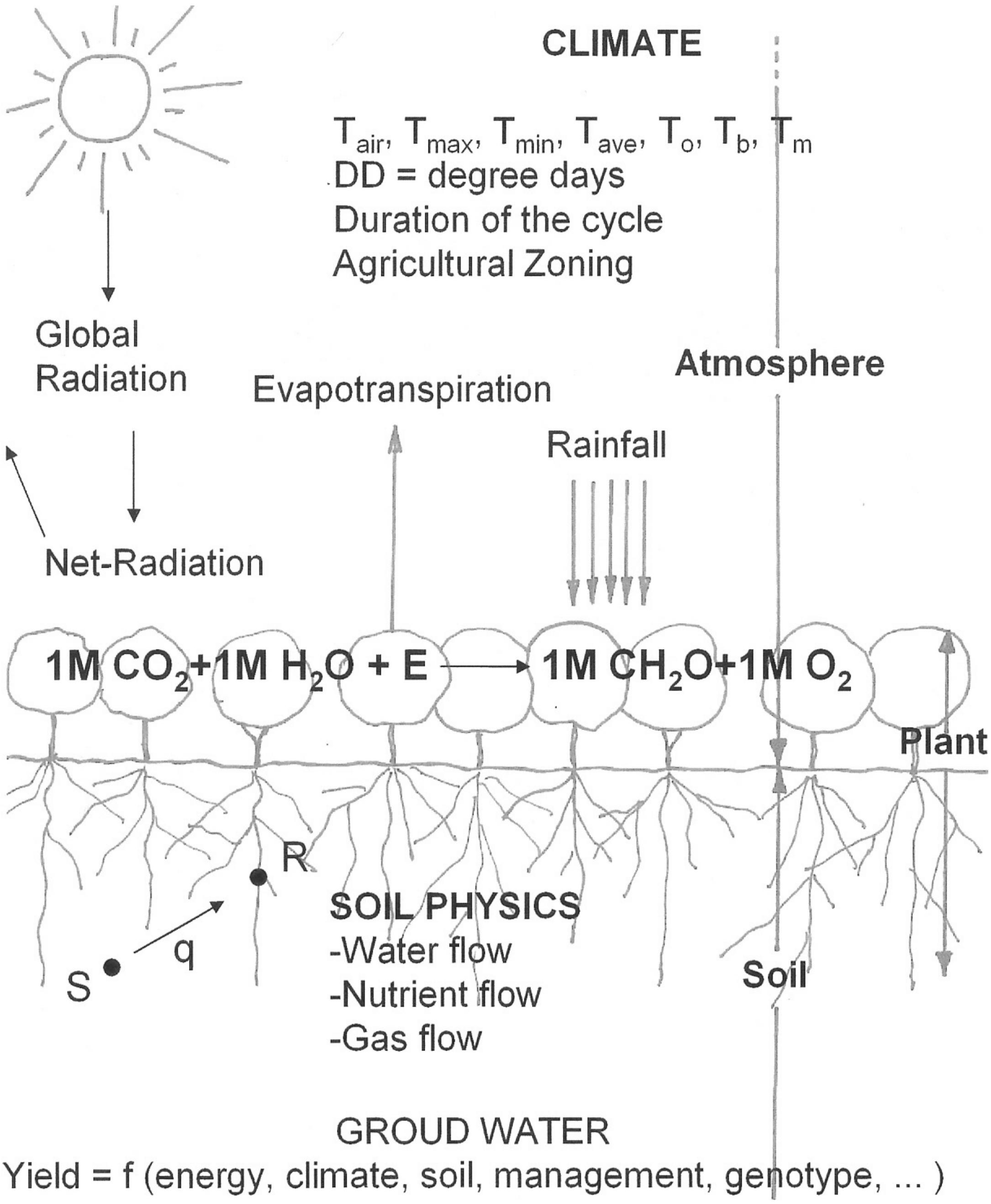

Figure 1. The Soil – Plant – Atmosphere system in relation to crop production.

The rate of assimilation of atmospheric CO_2 by plants RCA will finally determine the yield. RCA is defined as the mass or volume of CO_2 that is absorbed per unit area of crop projection on the ground, per unit of time, or kg m^{-2} day^{-1}.

In order to grow and live, plants also spend energy through the respiration process, which is essentially the inverse reaction, by which plant sugar is burned by oxygen resulting carbon dioxide and water. For a plant to build up in yield, the sugar production by photosynthesis has to overcome the sugar consumption by respiration, or respiration rate RR, measured in the same units as RCA. Figure 2 shows schematically the rates of these two processes as a function of T_{air} . The photosynthesis assimilation rate increases with temperature, passes through a maximum and decreases as the air becomes too warm. The respiration rate essentially increases linearly with temperature. Each plant species has its own and typical shape of Figure 2a. For temperatures below T_b, the lower basal temperature, the net CO_2 assimilation rate NCAR = [RCA – RR] becomes negative and the plant consumes its energy; for temperatures above T_m, the upper basal temperature the net assimilation rate becomes again negative. Within the temperature interval T_m - T_b, the plant accumulates yield, with an optimum at T_o , when the net assimilation rate is maximum.

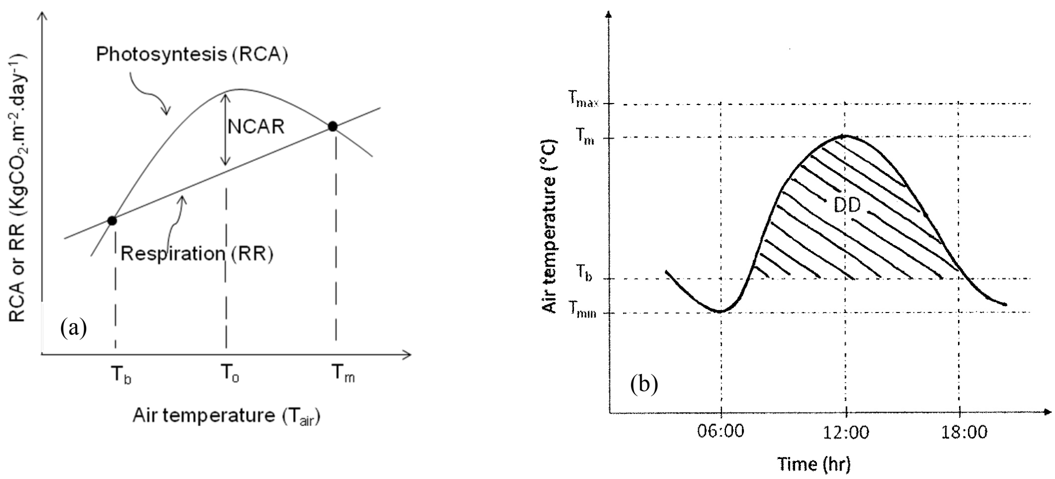

Figure 2. Temperature relations for plant growth: (a) Photosynthesis rate (RCA), respiration rate (RR), and net carbon assimilation rate (NCAR); (b) Degree Day (DD) concept for an equinox day in tropical/subtropical regions.

Plant growth models relate the available solar energy to the net carbon assimilation rate to evaluate crop growth curves. They can be very complex. Some simpler ways use the concept of degree-days DD is based on the air temperatures shown in Figure 2a. DD represents an area on the daily air temperature graph, limited by T_b and T_m (Figure 2b). There are several methods to estimate the area shown above, and the daily values of DD are summed up over the cropping cycle. The plant needs a total of energy to complete its life cycle and the summed DDs are conveniently used to follow the crop growth process. The warmer the climate, the quicker the plant sums-up the DDs necessary to complete its cycle. The adaptation of a given plant to a given climate is related to the DD sum.

The soil supplies rainfall or irrigation water (together with nutrients) to the plant. This water flows from the soil through the plant to the atmosphere, where its energy is lowest. The process is called evapotranspiration and depends on the atmospheric conditions. When the soil reservoir is at high water levels, evapotranspiration is maximal, and depends mostly on the atmospheric water demand. When soil water becomes short, soil physical characteristics play an important role and command the supply of water to the plant.

Soil water reaching roots carries along the mineral nutrients essential for crop growth and development. Therefore, yield depends also on the rates by which these nutrients are supplied to the plant.

As described above, the process of agricultural production is very complex and several factors affecting it are out of man´s control. Many, however, can be managed in order to maximize the yield of each crop in each region. The water balance gives an important overview of the water regime and is an essential tool for an effective crop management.

2. Elementary Volume and Balance Components

Considering the whole physical environment of a field crop, we define an elementary volume of soil to establish the water balance, having a representative unit surface area (1 m^2), and a height (or depth) ranging from the soil surface ($z = 0$) to the bottom of the root zone ($z = L$), where z (m) is the vertical position coordinate (Figure 3). In practice, the soil surface is never leveled or horizontal, in general presenting an ondulated relief with characteristic slopes in all directions. This complicates the definition of a horizontal soil surface plane at $z = 0$, and for our vertical water balance we consider $z = 0$ as a moving point A always following the soil surface, which does not mean that this plane is leveled.

We will consider only vertical water fluxes (or better water flux densities) along the vertical coordinate z. They correspond to amounts (volumes) of water that flow through unit cross-sectional areas, per unit of time. One convenient unit for agricultural purposes is liters (L) of water per square meter (m^2) per day, which corresponds to $mm.day^{-1}$:

$$1\ L = 10^3\ cm^3 = 10^6\ mm^3$$

$$1\ m^2 = 10^4\ cm^2 = 10^6\ mm^2$$

$$1\ L / m^2 = 10^6\ mm^3 / 10^6\ mm^2 = 1\ mm$$

These fluxes are assumed positive when entering the elementary volume (gain), and negative when leaving (loss).

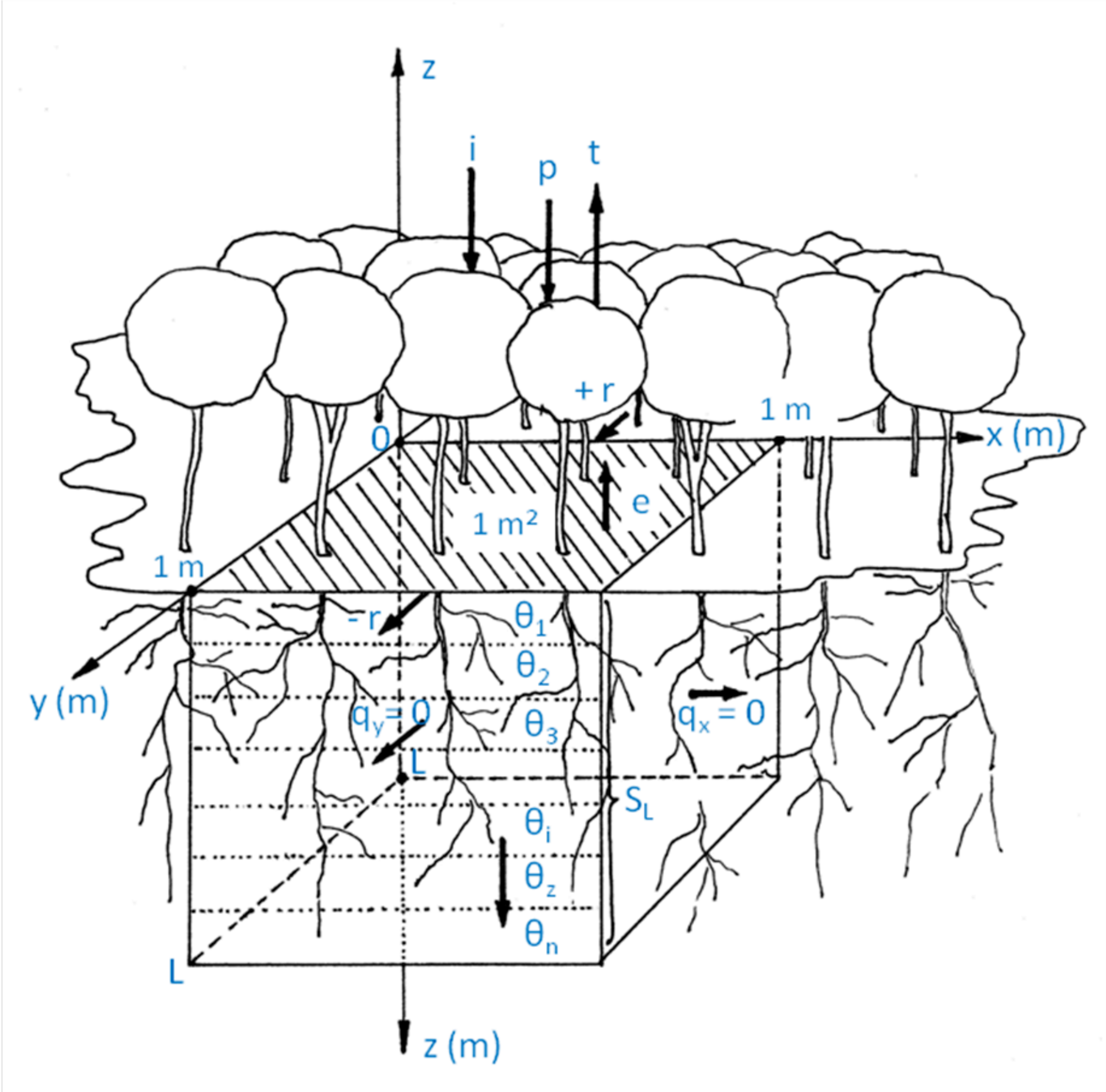

Figure 3. Schematic view of the volume element and of the fluxes that compose the water balance.

At the upper boundary plane or soil surface (Figure 3), of the elementary volume (z = 0), rainfall (**p**) and irrigation (**i**) are considered gains (in particular cases snow, after melted, is also an input, and in general, dew and other minor processes are considered negligible). Reaching soil surface, p or i either infiltrate (gain) or run-off (**-r**) the study area (loss) or run-in (**+r**) the study area (gain) in cases there is slope and no surface water control. Water evaporation from the soil surface (**e**), transpiration from plant surfaces (**t**), or evapotranspiration (**et = e + t**) are losses.

At the lower boundary plane (Figure 3), the bottom of the root zone at z = L, the soil water fluxes (**q_L**) can be gain (when upwards), sometimes called capillary flow, or loss (downward flow or drainage, sometimes called internal drainage), representing the deep drainage component. Inside the elementary volume (L m^3 = 1 m^2 x L m) we consider only soil water fluxes in the z direction q_z, so that lateral fluxes q_x and q_y (Figure 3) are considered zero (no lateral losses).

The change in soil water storage ΔS is the result of the balance, being positive when the profile has a net gain of water, and negative for a net loss. S is defined by Equation 2, bellow.

3.The Water Balance

The water balance is an expression of the mass conservation law, which includes the summation of all above discussed flux densities **f** that enter or leave the elemental volume:

$$\sum f = \int_0^L \frac{\partial \theta}{\partial t} dz \qquad (1)$$

where θ is the soil water content ($m^3.m^{-3}$) inside the elementary volume, t the time (day) and **f** stands for the flux densities **p**, **i**, **t**, **e** (or **et**), **r** and **q**. Their sum gives rise to changes in soil water contents ∂θ/∂t in time, which integrated over the depth interval of the elementary volume, z = 0 and z = L, represents the change in soil water storage S. Therefore, equation (1) can be rewritten as:

$$p + i - et \pm r \pm q_L = \frac{\partial S}{\partial t} \qquad (1a)$$

where S is defined by

$$S = \int_0^L \theta dz \qquad (2)$$

which by the trapezoidal rule becomes

$$S = \sum_{i=1}^{n} \theta_i \Delta z = [\theta_1 + \theta_2 + \theta_i + ... + \theta_n]\Delta z = \bar{\theta} L \qquad (2a)$$

and when expressing L in mm, S is also given in mm.

Equation 1a is an instantaneous view of the balance. When integrated over a time interval $\Delta t = t_f - t_i$, in days, it yields amounts of water (mm):

$$\int_{t_i}^{t_f} (p + i - et \pm r \pm q_L) dt = \int_{t_i}^{t_f} \int_0^L \frac{\partial \theta}{\partial t} dz dt \qquad (3)$$

or

$$P + I - ETa \pm R \pm Q_L = \Delta S = S(t_f) - S(t_i) \qquad (3a)$$

Equation 3a is an overtime integrated view of the water balance.

The time interval for integration $\Delta t = t_f - t_i$ (Equation 3) is chosen according to the objectives of the balance. Since water moves slowly in the soil, the choice of a too small Δt, e.g. less than 1 day, is seldom made. For annual crops common choices are 3, 7, 10, 15 or 30 days intervals. For long term experiments Δt can be of 1 year or more.

When all but one of the above components are known, the unknown is easily calculated algebraically. Five short examples are given below:

1. A soil profile stores 280 mm of water and receives 10 mm of rain and 30 mm of irrigation. It looses 40 mm by evapotranspiration. Neglecting runoff and soil water fluxes below the root zone, what is its new storage?
2. A soybean crop loses 35 mm by evapotranspiration in a period without rainfall and irrigation. It looses also 8 mm through deep drainage. What is its change in storage?
3. During a rainy period, a plot receives 56 mm of rain, of which 14 mm are lost by runoff. Deep drainage amounts to 5 mm. Neglecting evapotranspiration, what is the storage change?
4. Calculate the daily evapotranspiration of a bean crop which, in a period of 10 days, received 15 mm of rainfall and two irrigations of 10 mm each. In the same period, the deep drainage was 2 mm and the change in storage –5 mm.
5. How much water was given to a crop through irrigation, knowing that in a dry period its evapotranspiration was 42 mm and the change in storage was –12 mm? Soil was at field capacity and no runoff occurred during irrigation.

SOLUTIONS

n°	**P**	**+**	**I**	**-**	**ET**	**±R**	**±Q_L**	**=**	**ΔS_L**	**Answer**
1	10		30		-40	0	0		0	280 mm
2	0		0		-35	0	-8		-43	-43 mm
3	56		0		0	-14	-5		+37	+37 mm
4	15		20		-38	0	-2		-5	-3.8 $mm.day^{-1}$
5	0		30		-42	0	0		-12	+30 mm

As seen in the above discussion, WBs are very straight forward and their principle very simple. We have, however, assumed all components as deterministic values, without considering their variability in space and time. This is not the real case since all of them, when measured, present a stochastic behavior. Soils are not at all homogeneous so that infiltration, run off, run in and soil water fluxes vary from site to site, affecting the variability of S and ET. Climate elements like rainfall, air temperature and humidity, wind and solar energy also vary from site to site and in time. Plants vary a lot in spacing, height, leaf are and shape, rooting depth, variety, etc. This variability has been the subject of an enormous number of studies, first using classical statistics tools, involving mean values, medians, modes and variance analyses of all types. Somewhat later researchers started using tools of regionalized variables, geostatistics and state-space analysis. Therefore, the establishment of field WBs is not so straight forward as it is thought at first site. In the following item we will quickly discuss some of the main problems in evaluating WB components in light of their variability in time and space.

4.Discussion of the Components

4.1. Rainfall

Rainfall is easily measured with simple rain gauges which consist of containers of a cross sectional area A (m^2), which collect a volume V (liters) of rain, corresponding to a rainfall depth h (mm) equal to h = V/A. The problem in its measurement lies mostly in the variability of the rain in space and time. In the case of whole watersheds, rain gauges have to be well distributed, following a scheme based on rainfall variability data. For the case of small experimental fields, attention must be given to the distance of the gauge in relation to the water balance plots. Reichardt et al. (1995) is an example of a rainfall variability study, carried out in a tropical zone, where localized thunder-storms play an important role in the variability. Bruno et al. (2008) also discuss aspects of the number of rain gases to be used.

4.2.Irrigation

The measurement of the irrigation depth that effectively infiltrates into a given soil at a given place is not an easy task. Different methods of irrigation (sprinkler, furrow, drip, flooding, etc....) present great space variability in supplying water to the soil, which has to be taken into account.

4.3.Evapotranspiration (ET)

The loss of water through evapotranspiration occurs in the vapor phase, mainly through plant surface (stomata and cuticle) and through soil surface. Energy is needed to convert liquid water into vapor (latent heat that comes from the Sun and from the surrounding air). Some specific definitions are essential:

Potential Evapotranspiration (ET_0) or reference evapotranspiration is the loss of water to the atmosphere of a green, shortly cut grass surface, directly exposed to the prevailing low air layer, growing on a soil with its available water capacity full. Under such well defined conditions it is a reference value for the location, representing the potential water loss of the green surface at each particular climatic condition, without interference of the soil because its water is freely available to the grass.

Pan Evaporation EP is the loss of a free water surface, in general measured with a 1.2 m diameter pan exposed to the prevailing air conditions. In general, EP > ET_0 because in the pan the water is very free for the evaporation process. Since the measurement of is ET_0 is more difficult than EP, a pan coefficient K_p is used to transform one into the other:

$$ET_o = K_p.EP \qquad (4)$$

Maximum Evapotranspiration ET_m is the potential evapotranspiration of any crop (excluding grass), which follows the definition of ET_0. A crop coefficient K_c is used to obtain ET_m for any crop when ET_0 is known:

$$ET_m(\text{crop}) = K_c.ET_o(\text{grass}) \qquad (5)$$

Actual or Real Evapotranspiration ET_a is the evapotranspiration that occurs under any Soil-Plant-Atmosphere condition, and is the one presented in the Equation 3a of the water balance. When soil water is readily available $ET_a = ET_m$, and as the soil dries out, the water flow to roots becomes restricted mainly due the reduction in soil hydraulic conductivity, and ET becomes steadily lower than ET_m. The extraction of the soil water by plants decreases, therefore, exponentially, tending to reach the Permanent Wilting Point PWP if there is no addition of water by rain or irrigation. Evapotranspiration can be measured independently using lysimeters or estimated from the balance, if all other components are known. For the measurement of ET_0, a great number of reports can be found in the literature, covering classical methods like those proposed by Thornthwaite, Braney-Criddle and Penmann-Monteith, which are based on atmospheric parameters such as air temperature and humidity, wind, solar radiation, etc. These methods have all their own shortcomings, mainly because they do not take into account plant and soil factors. Several models, however, include aspects of plant and soil, and yield much better results.

The main problem of estimating ETa from the balance lies in the separation of the contribution of the components ETa and Q_L, since both lead to negative changes in soil water storage ΔS. One important thing is that the depth L has to be such that it includes the whole root system. If there are roots below z = L, ET_a is under estimated. If L covers the whole root system and Q_L is well estimated, which is difficult as will be seen below, ETa can be estimated from the balance. Villagra et al. (1995) discuss these problems in detail.

4.4.Runoff (R)

Runoff is difficult to be estimated since its magnitude depends on several factors, mainly rainfall intensity and duration, slope of the land, length of the slope, soil type, soil cover, etc. For very mild slopes, runoff is in general neglected. If the soil is managed correctly, using contour lines, even with significant slopes runoff is controlled and can be neglected. In cases it cannot be neglected, runoff is measured using small plots like ramps which are surrounded by a metal frame to maintain the rainfall water inside, about 20 m long and 2 m wide, covering areas from 40 to 50 m^2, with a water collector at the lower end. Again, the runoff depth h (mm) is the volume V (liters) of the collected water, divided by the area A (m^2) of the ramp. Several reports in the literature cover the measurement of R, either directly or through models (equations), and its extrapolation to different situations of soil, slope, cover, etc. This is a very well considered topic in other opportunities of this College.

4.5.Soil Water Fluxes at z = L, Q_L

The estimation of soil water fluxes at the lower boundary z = L, can be estimated using Darcy-Buckingham´s equation, integrated over the time:

$$Q_L = \int_{ti}^{tf} \left[K(\theta) \partial H / \partial z \right] dt \qquad (6)$$

where $K(\theta)$, ($mm.day^{-1}$), is the hydraulic conductivity estimated at the depth z = L, and $\partial H/\partial z$ ($m.m^{-1}$) the hydraulic potential head gradient, H (m) being assumed to be the sum of the gravitational potential head z (m), and the matric potential head h (m). Therefore it is necessary to measure $K(\theta)$ at z = L and the most common procedures used are those presented by Hillel et al. (1972), Libardi et al. (1980), Sisson et al. (1980), and more recently by Reichardt et al. (2003) These methods present several problems, discussed in detail in Reichardt et al. (1998). The use of these $K(\theta)$ relations involves two main constraints: (i.) the strong dependence of K upon θ, which leads to exponential or power models, and (ii.) soil spatial variability.

Two commonly used K(θ) relations are:

$$K = K_o \exp[\beta(\theta - \theta_o)] \quad (7)$$

and

$$K = a\theta^b \quad (8)$$

in which β, a and b are parameters obtained by fitting experimental data to the models, K_o the saturated hydraulic conductivity, and θ_o the soil water content at saturation. Reichardt et al. (1993) used Model 7, and for 25 observation points of a transect on a homogeneous dark red latosol, obtained an average equation with $K_{oaverage} = 144.38 \pm 35.33$ mm.day^{-1}, and $\beta_{average} = 111.88 \pm 33.16$, obtaining an average equation:

$$K = 144.38 \exp[\,111.88(\theta - 0.442)] \quad (7a)$$

in which $\theta_o = 0.442$ m^3.m^{-3}.

To understand the difficulties in using this average equation in the estimation of soil water fluxes, let's take an example in which the soil water content at the point we are making our calculations is θ = 0.4 m^3.m^{-3}. Applying Equation 7a we obtain K = 1.04 mm. day^{-1}. If this value of θ has an error of 2%, which is very small for field conditions, we could have θ ranging from 0.392 to 0.408 m^3.m^{-3}, and the corresponding values of K by applying Equation 7a are: 0.43 and 2.55 mm.day^{-1}, with a difference of almost 500%, which means that in our flux calculation we will have very large error. This example shows in a simple manner the effect of the exponential character of the K(θ) relations. The standard deviations of K_o and β, shown above, reflect the problem of soil spatial variability in calculating soil water fluxes in WB studies. Added to this is the spatial variability of θ itself. Therefore, the direct measurement of Q_L using Darcy's equation is a difficult task, and several indirect methods have been suggested in the literature. Again, if we measure well all other water balance components of Equation 3a, Q_L could be left as an unknown in the equation.

6.Changes in Soil Water Storage ΔS

Soil water storage S, defined by Equation 9 is, in general, estimated either by: (i) direct auger sampling; (ii) tensiometry, using soil water characteristic curves; (iii) using neutron probes; and (iv) using TDR probes. The direct sampling is the most disadvantageous due to soil perforations left behind after each sampling event. Tensiometry embeds the problem of the establishment of soil water characteristic curves, and neutron probes and TDR have calibration problems.

Once θ versus z data at fixed times are available, S is estimated by numerical integration, the trapezoidal rule being an excellent approach, and in this case, Equation 2 becomes:

$$S = \int_0^L \theta dz \cong \sum \theta \Delta z = \bar{\theta} L \qquad (9)$$

The changes ΔS are simply the difference of S values obtained at the different times t_i and t_f, that is $S(t_f)$-$S(t_i)$ as shown in Equation 3a.

A recent discussion of the establishment of field water balances is found in Silva et al. (2006) and Silva et al. (2007). The same data presented in these two papers was further analysed by Timm et al. (2010), using the state-space or better state-time analysis, indicating that this methodology presents several advantages over the classical statistical analysis.

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VARIABILITY OF WATER BALANCE COMPONENTS IN A COFFEE CROP GROWN IN BRAZIL

ABSTRACT

The establishment of field water balances is difficult and costly, the variability of its components being the major problem to obtain reliable results. This component variability is here presented for a coffee crop grown in the Southern Hemisphere, on a tropical soil with 10% slope. It is concluded that rainfall has to the measured with an appropriate number of replicates, that irrigation can introduce great variability into calculations, that evapotranspiration calculated from the water balance equation has too high coefficients of variation, that the soil water storage component is the major contributor in error propagation calculations, and that the run-off could be satisfactorily controlled on the 10% slope through crop management practices.

Keywords: water balances; component variability; rainfall; evapotranspiration; soil water storage.

1. Introduction

Water balances are of extreme importance to follow water dynamics in agricultural and natural ecosystems. They indicate, in space and time, the conditions under which plants grow and develop, being useful in the interpretation of plant behavior during periods that differ from the normal climatic condition of the place in question, such as periods of water excess or deficit. These aspects are of great importance for crop management and the understanding of the behavior of natural ecosystems. A non-response of a crop to a fertilizer or the disappearance of a given natural species, can be partially explained in light of consistent water balances.

The coffee crop is among the most important crops in Brazil, being cultivated over an area of almost 3 million ha, with a production of 34 million bags of dry beans (60 Kg each) per year (FNP, 2002). Among the several factors that affect the productivity of this crop, of extreme importance are the water relations in the soil-plant-atmosphere system and the availability of nutrients, mainly nitrogen. The establishment of water balances is an excellent tool to better understand these water relations with respect to the growth and development of the crop, and to quantify important nitrogen losses by leaching, volatilization and run-off.

The establishment of field water balances is time consuming and costly due to the required equipment. For this reason they are seldomly replicated in order to obtain significant average values. Since the water balance is an addition of several components, each of them having its own space and time variability, error propagation can lead to inconsistent results. Villagra et al. (1995) discuss this variability problem in a study comprising 25 balance replicates, their main problem being the estimation of soil water fluxes below the root-zone.

With the objective of contributing to a better understanding of water relations of the coffee crop, we present the variability of the water balance components, using five replicates distributed within a 0.2ha coffee crop.

2. Material and Methods

2.1. Experimental Field

The experiment was carried out in Piracicaba, SP, Brazil, (22^{o}42\`S, 47$^o$38\`W, 580m above sea level) on a soil classified as Rhodic Kandiudalf, locally called “Nitossolo Vermelho Eutroférrico”, A moderate and clayey texture. The climate is Cwa, according to Köppen’s classification, mesothermic with a dry winter, in which the average temperature during the coldest month is below 18^{o}C and during the hottest month, is over 22^{o}C. The annual average temperatures, rainfall, and relative humidity are 21.1^{o}C, 1,257 mm, and 74%, respectively. The dry season is between April and September; July is the driest month along the year. The wettest period is between January and February. The amount of rainfall during the driest month is not over 30 mm (Villa Nova, 1989).

Coffee plants (*Coffea arabica* L.), cultivar “Catuaí Vermelho” (IAC-44) were planted in line along contour-lines in May 2001. The spacing in rows was 1.75 m and 0.75 m between plants. The total coffee area of 0.2 ha was divided into 15 plots with nearly 120 plants each. This arrangement was used in order to distribute randomly three treatments of a parallel Nitrogen Balance study, with five replicates.

The experimental evaluations started on September 1, 2003 at 8:00 am. The following dates received the code DAB (days after beginning, since the crop is perenial) followed by the number of days. It is important to mention that a field day starts at 8:00 am and finishes in the following day at 8:00 am.

Only the five replicates of the treatment with highest rate of N-fertilizer (T_2) were used in order to establish the water balances, made in sub-plots with nine plants covering an area of 11.8125 m^2, on a 10 ± 2 % slope. These plots were fenced to perform the nitrogen balance, fertilizing the area with enriched ammonium sulphate. The experimental area is located under the edge of a central-pivot irrigation system which, therefore, did not permit very regular applications of water depths. An automatic meteorological station was installed nearby (about 200 m). The experimental design, used in the parallel N study consisted of randomized blocks with three treatments of N, T_0, T_1 (1/2 rate), and T_2 (1 rate), receiving 280 $kg.ha^{-1}$ of N split into 4 applications (DAB-0, DAB-63, DAB-105, and DAB-151), with a regular P and K fertilization.

2.2. Water Balance

Water balances started on September 1, 2003 (DAB-0) and continued to be established for 14 day periods ($\Delta t = t_{i+14} - t_i$), continually, until August 30, 2004 (DAB-364), completing one year. The classical water balance equation representing the mass conservation law was used, considering water fluxes entering and leaving a soil volume element, integrated over time for 14 day periods, $\Delta t = t_{i+14} - t_i$:

$$\int_{t_i}^{t_{i+14}} p dt + \int_{t_i}^{t_{i+14}} i dt - \int_{t_i}^{t_{i+14}} e dt - \int_{t_i}^{t_{i+14}} r dt \pm \int_{t_i}^{t_{i+14}} q_L dt + S_{i+14} - S_i = 0 \qquad (1)$$

which by solving the integrals results in:

$$P + I - ETa - RO - Q_L + \Delta S = 0 \qquad (2)$$

where P = rainfall; I = irrigation; Eta = actual evapotranspiration; $\Delta S = S_{i+14} - S_i$ = soil water storage changes in the soil 0–L layer; RO = runoff; and Q_L = deep drainage at the lower boundary of the soil volume at the depth z = L, all expressed in mm.

Rainfall (P) was measured daily and integrated over Δt at each replicate, using traditional rain-gauges (“Ville de Paris”) with 0.04047 m^2 collecting areas, installed in the sub-plots 1.2 m above soil surface. Due to the presence of obstacles in the neighborhood of the experimental area, such as, a silo, a warehouse, orchards, and tall trees, the rainfall was measured in each T_2 plot using 5 rain-gauges, opening the possibility of obtaining average values ($\overline{P}$) with standard deviations [s(P)] and coefficients of variation (CV).

Irrigation for coffee in this region of Brazil is supplementary, applied only during periods of severe drought, in our case through the central-pivot system. As mentioned above, the coffee crop plots were at the edge of this irrigation system, which increased the variability of water application. This variable was also measured by the 5 rain-gauges installed for rainfall measurement.

The criteria of amount and time of irrigation were mostly based on physiological aspects of the coffee plant that requires a cold and dry winter to blossom, which starts after the first significant rain. After blossoming, an excessive lack of water may cause flower loss. Therefore, the decision to irrigate was taken by visual observation of the water deficit, trying to apply 30 mm of water depth that approximately would wet a 0.6 m soil layer.

The actual crop evapotranspiration (ETa) was estimated by difference from all other components, using equation (2). In wet periods, with a drainage (Q_L) likely to happen and considering it as zero in equation (2), ETa, now named ETa', was overestimated because it includes Q_L. Thus, in periods in which ETa was larger than the potential evapotranspiration (ETm), ETa was considered equal to ETm and the difference ERa–ETm = Q_L. The potential evapotranspiration was estimated from the reference evapotranspiration (ET_0) corrected by the crop coefficient (K_C). ET_0 was calculated using Penman-Monteith equation (Pereira et al., 1997), with meteorological data collected at the automatic weather-station installed near the experimental area. K_C was calculated by dividing ETa by ET_0 along the periods in which the plants were not under stress, when the soil water storage was relatively high and without drainage. The above referred K_C was the average value obtained for these periods.

Since ETa was calculated from the balance equation (2) its variability was estimated through error propagation:

$$s^2(ETa') = s^2(P) + s^2(I) + s^2(RO) + s^2(S_{i+14}) + s^2(S_i) \qquad (3)$$

and $s(Q_L)$ was taken equal to $s(ETa')$ since it was calculated by the difference ER'-ET, considering ET an absolute value.

The soil layer 0-1m (L=1m) was chosen to calculate soil water storages $S(t_i)$ since at this stage of the crop this soil layer contains more than 95% of the root system. $S(t_i)$ was estimated from soil water content measurements ($\theta, m^3.m^{-3}$) obtained by a neutron probe, using three access tubes installed down to the depth of 1.2 m in each plot, making up a total of 15 tubes. The calibration of this probe, model CPN 503 DR, was made in an area close to the experimental field. The moisture contents were measured at 0.20, 0.40, 0.60, 0.80, and 1.00 m at the selected dates t_i, during the experimental period, which started at t_i (DAI-0) and continued up to t_{i+14}, Δt = 14 days. $S(t_i)$ was calculated using the trapezoidal rule:

$$S(t_i) = \int_0^L \theta(t_i)dz = [\overline{\theta}(t_i)].L \qquad (4)$$

where $\overline{\theta}(t_i)$ is the average θ at time t_i and the soil depth L, in this case taken as 1,000 mm in order to obtain S expressed in mm.

For measuring the runoff, each experimental plot was framed by metal dicks, and the water was collected by gravity in 60L tanks placed downslope.

3. Results and Discussion

3.1. Rainfall (P)

The accumulated values of P for each water balance period (14 days) are presented on the Table 1. Despite rain-gauges being relatively near to each other (15 to 100 m apart), there was a significant variability among the readings performed over the five replicates. Generally speaking, the CV values were low (2 - 4%), but some of them presented higher values, mainly those from water balances 2, 16, and 22, with CVs over 10%. For balances 2 and 22 this can be explained through the low amounts of rainfall, and balance 16 has an unexplained out-layer of 78.6mm in an average of 65.2mm.

This data variability justifies the need for measuring P in replicates as made in this study. Reichardt et al (1995) discuss the problem of rainfall variability using the city of Piracicaba as an example. They also demonstrated that spatial variability has to be taken into consideration and that rainfall has to be measured as close as possible to the experimental area as it was made in this study, mainly for short time periods like 14 days.

During the whole agricultural year, balances 1 to 26, the total amount of rainfall was a little higher than 1,275 mm, the historic rainfall average for the region, revealing that the year under study was within the normal rainfall parameters.

3.2. Irrigation (I)

As mentioned before, the irrigation was supplementary and applied only to avoid water deficits which could irreversibly damage the crop. In the Piracicaba region, irrigation practices are not part of the coffee crop management.

Table 1. Average rainfall (P), standard deviations [s(P)], and coefficients of variation (CV) of each period.

Balance	Period	DAB	Rainfall (P)							
			1	2	3	4	5	$\overline{P}$	s(P)	CV
1	01/09 to 15/09	0_14	4.0	4.2	4.3	4.2	4.0	4.1	0.1	3.2
2	15/09 to 29/09	14_28	5.8	5.8	6.4	4.8	6.2	5.8	0.6	10.6
3	29/09 to 13/10	28_42	79.0	75.4	80.6	78.0	75.9	77.8	2.2	2.8
4	13/10 to 27/10	42_56	18.2	18.1	18.2	17.6	17.5	17.9	0.3	1.9
5	27/10 to 10/11	56_70	25.4	24.9	26.3	24.5	25.5	25.3	0.7	2.7
6	10/11 to 24/11	70_84	75.7	74.2	78.7	74.2	72.5	75.1	2.3	3.1
7	24/11 to 08/12	84_98	93.9	88.9	91.8	87.4	86.7	89.7	3.0	3.4
8	08/12 to 22/12	98_112	51.0	49.8	49.3	48.5	48.0	49.3	1.2	2.4
9	22/12 to 05/01	112_126	89.2	86.5	85.1	84.4	82.8	85.6	2.4	2.8
10	05/01 to 19/01	126_140	52.4	51.1	50.5	49.6	49.3	50.6	1.2	2.5
11	19/01 to 02/02	140_154	173.7	168.4	165.7	166.7	164.2	167.7	3.7	2.2
12	02/02 to 16/02	154_168	73.9	71.4	69.1	67.9	66.9	69.8	2.8	4.0
13	16/02 to 01/03	168_182	156.6	156.3	153.7	149.2	148.8	152.9	3.7	2.5
14	01/03 to 15/03	182_196	75.9	74.8	72.2	71.4	71.2	73.1	2.1	2.9
15	15/03 to 29/03	196_210	14.4	14.4	14.0	13.8	13.2	14.0	0.5	3.6
16	29/03 to 12/04	210_224	59.4	78.6	62.2	65.0	61.0	65.2	7.7	11.9
17	12/04 to 26/04	224_238	54.7	53.6	51.8	50.9	50.7	52.3	1.7	3.3
18	26/04 to 10/05	238_252	23.9	24.1	22.9	22.3	22.7	23.2	0.8	3.4
19	10/05 to 24/05	252_266	27.4	27.2	25.1	23.9	24.1	25.5	1.7	6.5
20	24/05 to 07/06	266_280	105.5	104.5	101.1	98.5	97.7	101.5	3.5	3.4
21	07/06 to 21/06	280_294	7.6	8.0	7.1	6.7	6.5	7.2	0.6	8.7
22	21/06 to 05/07	294_308	2.4	2.0	1.8	1.6	1.6	1.9	0.3	17.8
23	05/07 to 19/07	308_322	33.2	33.1	32.5	32.2	32.3	32.7	0.5	1.4
24	19/07 to 02/08	322_336	46.8	45.4	43.9	43.6	43.1	44.6	1.5	3.4
25	02/08 to 16/08	336_350	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	16/08 to 30/08	350_364	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum	01/09 to 30/08	0-364	1350.0	1340.7	1314.3	1286.9	1272.4	1312.9	33.4	2.5

The dry period during the winter extends from July to September in Piracicaba and, during this period, the coffee plants are subject to water deficit and, as a physiological response, a high proportion of the leaves drop. At the end of this period, rain triggers blossoming and continued water deficit can affect flower setting, making irrigation necessary. At the beginning of the experiment (DAI=0) the coffee plants were under a strong water deficit and for this reason, even with a small rainfall (4.1 mm), irrigation was applied, as shown in Table 2. The variability of this irrigation was even greater than that of the rainfall (CV=35.1%) due to the factors previously mentioned: edge of the central-pivot, wind drift, obstacles, etc. According to the chosen speed for the central-pivot, the amount applied should have been 30 mm, which is very different from the measured values shown in Table 2.

During the following winter (2004), another additional irrigation was needed during water balance 26 for the same reasons mentioned before. The variability, this time, presented a CV of 41.7%.

Despite the difficulties occurred during irrigation, the total amount of water applied artificially was very small in relation to the total amount of rainfall and the irrigation variability affected only the estimates of two water balances (1 and 26). The irrigations were necessary for relieving the coffee crop from the water stress that occurred during those periods.

Table 2. Average irrigation $(\bar{I})$, standard deviations s(I), and coefficients of variation (CV) for two periods.

Balance	Period	DAB	Irrigation		
			$\bar{I}$	s(I)	CV
1	01/09 to 15/09	0_14	34.2	12.0	35.1
26	16/08 to 30/08	350_364	37.5	15.6	41.7

3.3. Actual Evapotranspiration (ETa)

Table 3 presents ETa' data together with s(ETa'), CV, ET_0, K_C, ET_C, the evapotranspiration corrected by drainage ER, and Q_L. Water balances 5 to 22 were chosen to estimate Kc by means of the relation ETa/ET_0. During these balances soil water storage S_L was high enough to assume that plants had no restriction to soil water and that differences between ETa and ET_0 are due to plant architecture and to percent of crop cover. Exception was made to balances 11, 13 and 20, during which drainage Q_L occurred. The variability of K_C is large, ranging from 0.6 and 1.7, with an average of 1.1, standard deviation 0.3, and CV=31.2%. In order to complete the K_C column on Table 3, the average Kc was considered for the water balances under water deficit and with drainage.

The highest ETa value was the one obtained in balance 12, of 6.8 mm.day^{-1}, which is a coherent value for February in Piracicaba. The lowest values occurred on the balances 2, 23, and 25, with 0.9, 0.5, and 0.8 mm.day^{-1}, respectively. During these periods, coffee plants were under water deficit and, consequently, losing their leaves.

Table 3. Average actual evapotranspiration (ETa'), its standard deviation [s(ETa') calculated through equation 03], reference evapotranspiration (ET_0), crop coefficient (K_C), potential evapotranspiration (ETm), and the drainage below root zone (Q_L) for each period.

Balance	DAB	$\overline{ETa'}$ (mm)	s(ETa')	CV	$\overline{ET_0}$ (mm)	K_C	$\overline{ETm}$ (mm)	$ETa=ETa'-Q_L$ (mm)	$\overline{Q_L}$ (mm)
1	0_14	-26.1	33,65	129,0	-45.9	1.1	-50.1	-26.1	0,0
2	14_28	-11.9	29,92	250,9	-56.0	1.1	-61.2	-11.9	0,0
3	28_42	-50.9	31,25	61,3	-53.9	1.1	-58.9	-50.9	0,0
4	42_56	-24.8	32,00	129,1	-65.4	1.1	-71.5	-24.8	0,0
5	56_70	-33.1	33,19	100,3	-47.5	0.7	-33.1	-33.1	0,0
6	70_84	-62.3	32,90	52,8	-60.3	1.0	-62.3	-62.3	0,0
7	84_98	-72.0	30,74	42,7	-50.5	1.4	-72.0	-72.0	0,0
8	98_112	-57.5	31,10	54,1	-62.4	0.9	-57.5	-57.5	0,0
9	112_126	-68.1	33,87	49,7	-57.5	1.2	-68.1	-68.1	0,0
10	126_140	-52.2	33,28	63,7	-63.2	0.8	-52.2	-52.2	0,0
11	140_154	-97.4	33,95	34,9	-39.3	1.1	-42.9	-42.9	-54,4
12	154_168	-95.5	34,66	36,3	-62.0	1.5	-95.5	-95.5	0,0
13	168_182	-130.6	35,80	27,4	-46.8	1.1	-51.2	-51.2	-79,4
14	182_196	-89.3	36,28	40,6	-52.3	1.7	-89.3	-89.3	0,0
15	196_210	-62.4	33,95	54,4	-55.3	1.1	-62.4	-62.4	0,0
16	210_224	-64.2	33,61	52,4	-47.7	1.3	-64.2	-64.2	0,0
17	224_238	-51.7	32,31	62,5	-36.1	1.4	-51.7	-51.7	0,0
18	238_252	-29.6	33,03	111,6	-35.6	0.8	-29.6	-29.6	0,0
19	252_266	-25.6	32,92	128,8	-24.4	1.0	-25.6	-25.6	0,0
20	266_280	-46.8	30,75	65,6	-23.4	1.1	-25.6	-25.6	-21,3
21	280_294	-19.6	31,51	160,5	-29.9	0.7	-19.6	-19.6	0,0
22	294_308	-21.9	33,59	153,2	-35.4	0.6	-21.9	-21.9	0,0
23	308_322	-6.6	31,13	469,1	-27.7	1.1	-30.2	-6.6	0,0
24	322_336	-57.5	30,00	52,2	-35.7	1.1	-39.0	-39.0	-18,5
25	336_350	-11.4	30,48	266,5	-45.1	1.1	-49.3	-11.4	0,0
26	350_364	-46.1	30,26	65,7	-46.7	1.1	-51.0	-46.1	0,0
1_26	0_364	-1315,3	-	-	-1206,0	1.1	-1318,3	-1141,7	-173,6

Table 4 presents the calculation of the standard deviation $s(ER')$ of the actual evapotranspiration, calculated through error propagation since this component was obtained as an unknown in Equation 2. From this table it can be seen that the greatest contribution to $s(ER')$ comes from $S(t_i)$ measurements. As a result $s(ETa')$ is very large in relation to its average ER', indicated by the high CVs presented in Table 3. They varied from 27.4% to 469.1%, showing a great uncertainity in measuring actual evapotranspiration from water balances. Most of the high CVs correspond to wet periods, when ER was close to ETc, periods during which aerodynamic models like the combined methods of Penman, Slatyer & McIlroy, and Penman-Monteith (Pereira et al., 1997), give much better

Table 4. Estimation of the standard deviation s(ETa') of the actual evapotranspiration ETa', using error propagation (Equation 3).

Balance	**DAB**	**s(P)**	**s(I)**	**s(S_F)**	**s(S_I)**	**s(RO)**	**s(ETa')**
1	0_14	0,1	12,0	20,7	23,7	0,0	33,6
2	14_28	0,6	0,0	21,6	20,7	0,0	29,9
3	28_42	2,2	0,0	22,5	21,6	0,3	31,2
4	42_56	0,3	0,0	22,8	22,5	0,0	32,0
5	56_70	0,7	0,0	24,1	22,8	0,0	33,2
6	70_84	2,3	0,0	22,3	24,1	0,4	32,9
7	84_98	3,0	0,0	21,0	22,3	0,3	30,7
8	98_112	1,2	0,0	22,9	21,0	0,0	31,1
9	112_126	2,4	0,0	24,8	22,9	0,8	33,9
10	126_140	1,2	0,0	22,1	24,8	0,1	33,3
11	140_154	3,7	0,0	25,5	22,1	0,7	33,9
12	154_168	2,8	0,0	23,3	25,5	0,4	34,7
13	168_182	3,7	0,0	26,9	23,3	1,1	35,8
14	182_196	2,1	0,0	24,3	26,9	0,7	36,3
15	196_210	0,5	0,0	23,7	24,3	0,0	34,0
16	210_224	7,7	0,0	22,5	23,7	0,3	33,6
17	224_238	1,7	0,0	23,1	22,5	0,1	32,3
18	238_252	0,8	0,0	23,6	23,1	0,1	33,0
19	252_266	1,7	0,0	22,9	23,6	0,0	32,9
20	266_280	3,5	0,0	20,2	22,9	1,1	30,7
21	280_294	0,6	0,0	24,2	20,2	0,0	31,5
22	294_308	0,3	0,0	23,3	24,2	0,0	33,6
23	308_322	0,5	0,0	20,6	23,3	0,1	31,1
24	322_336	1,5	0,0	21,7	20,6	0,0	30,0
25	336_350	0,0	0,0	21,4	21,7	0,0	30,5
26	350_364	0,0	15,6	14,7	21,4	0,7	30,3

estimatives. We, therefore, do not recommend the estimation of ER through water balances, a fact that does not depreciate water balances, since they are useful in many water management practices, reflecting in space and time, the water availability to the crop.

3.4. Soil water storage $S_L(t_i)$

Table 5 shows the variability of the soil water storage (S_L) calculated through the trapezoidal rule (Equation 4) from soil water content (θ) data collected by the neutron probe. The CVs are relatively low and very consistant. Since three access tubes were placed in each plot, each average $\overline{S_L}$ is the result of 15 measurements, that should be a good estimative of the soil water situation at the moment t_i. Neutron probes have the advantage over the classical methodologies of allowing measurements along time at exactly the same positions. This explains the homogeneity of the CVs. The variability of the data shown in Table 5 is a picture of the soil water variability of the experimental field. Using the conventional methods, such as auger sampling, it would not be possible to measure θ always at the same positions. This fact would increase a lot the variability of the data and would require a much larger experimental area due to the destructive samplings.

Through an analysis of Table 5 one can see that the lowest value S_{Lmin} is for balance 1 (245.2mm) corresponding to a severe water stress condition, but still high enough to maintain the crop growing. The maximum S_{Lmax} refers to balance 12 (369.9 mm), corresponding to the wettest condition, in which there was even drainage. With these extreme values the available water capacity of this soil profile (S_{Lmax}-S_{Lmin}) can be evaluated. This difference is 125 mm, which represents the maximum possible variation of S_L in this crop down to the depth of 1 m, for this particular soil.

3.5. Runoff (RO)

The runoff was very small in relation to the other components (1.7% in relation to rainfall) and presented a great variability, not appearing in all plots and in an unconsistant way. This means that the coffee crop planted on a 10% slope along contour-lines was adequate for runoff control and, consequently, erosion.

The high CVs presented in table 6 have to be analysed carefully. The presence of many null values may indicate that this variable probably does not follow the normal distribution and with very low mean values, CVs tend to increase by definition, even when the variable is correctly measured.

Anyway, the absolute values of RO were very small and affected very little the establishment of water balances.

Table 5. Soil water storage $S_L(t_i)$, standard deviations $s(S_L)$, and coefficients of variation (CV) of each period analyzed.

Balance	**Period**	**DAB**	**S_l**							
			1	**2**	**3**	**4**	**5**	$\overline{S_L}$	**$s(S_L)$**	**CV**
1	01/09 to 15/09	0_14	250.2	260.8	203.4	254.6	257.2	245.2	23.7	9.7
2	15/09 to 29/09	14_28	261.0	271.1	221.0	265.6	268.3	257.4	20.7	8.0
3	29/09 to 13/10	28_42	255.9	265.6	213.1	259.3	262.4	251.3	21.6	8.6
4	13/10 to 27/10	42_56	272.3	284.5	242.8	303.0	286.9	277.9	22.5	8.1
5	27/10 to 10/11	56_70	269.9	280.3	232.8	292.2	279.9	271.0	22.8	8.4
6	10/11 to 24/11	70_84	263.2	276.0	221.5	278.7	276.8	263.3	24.1	9.2
7	24/11 to 08/12	84_98	273.0	287.4	238.7	296.3	282.5	275.6	22.3	8.1
8	08/12 to 22/12	98_112	286.3	306.7	262.3	317.2	293.1	293.1	21.0	7.2
9	22/12 to 05/01	112_126	277.9	299.8	249.8	309.2	288.0	284.9	22.9	8.0
10	05/01 to 19/01	126_140	288.3	312.9	271.4	336.9	299.9	301.9	24.8	8.2
11	19/01 to 02/02	140_154	288.0	311.4	270.2	328.0	303.2	300.2	22.1	7.4
12	02/02 to 16/02	154_168	380.0	380.2	324.5	384.3	380.6	369.9	25.5	6.9
13	16/02 to 01/03	168_182	352.1	354.8	302.6	359.5	350.8	344.0	23.3	6.8
14	01/03 to 15/03	182_196	375.4	382.3	317.4	375.2	375.3	365.1	26.9	7.4
15	15/03 to 29/03	196_210	356.2	364.1	305.4	359.2	357.7	348.5	24.3	7.0
16	29/03 to 12/04	210_224	310.5	314.4	258.0	311.5	306.0	300.1	23.7	7.9
17	12/04 to 26/04	224_238	304.5	317.2	261.9	315.4	305.2	300.8	22.5	7.5
18	26/04 to 10/05	238_252	305.0	313.3	261.0	318.2	309.2	301.3	23.1	7.7
19	10/05 to 24/05	252_266	301.0	306.4	253.0	308.7	305.4	294.9	23.6	8.0
20	24/05 to 07/06	266_280	300.2	304.8	254.3	306.1	308.8	294.8	22.9	7.8
21	07/06 to 21/06	280_294	360.1	359.9	312.8	356.2	354.3	348.7	20.2	5.8
22	21/06 to 05/07	294_308	348.4	348.7	293.3	342.0	348.7	336.2	24.2	7.2
23	05/07 to 19/07	308_322	327.7	327.7	274.8	321.6	329.2	316.2	23.3	7.4
24	19/07 to 02/08	322_336	350.7	345.4	306.0	353.7	355.3	342.2	20.6	6.0
25	02/08 to 16/08	336_350	341.4	334.6	290.7	337.9	341.7	329.3	21.7	6.6
26	16/08 to 30/08	350_364	334.1	324.3	280.4	322.9	327.4	317.8	21.4	6.7

Table 6. Runoff (RO), standard deviations (SD), and coefficients of variation (CV) from each period.

Balance	Period	DAB	RO (mm)					$\overline{RO}$ (mm)	s(RO)	CV
			1	2	3	4	5			
1	01/09 to 15/09	0_14	-	-	-	-	-	-	-	-
2	15/09 to 29/09	14_28	-	-	-	-	-	-	-	-
3	29/09 to 13/10	28_42	0.0	0.0	0.4	0.6	0.1	0.2	0.3	118.9
4	13/10 to 27/10	42_56	0.0	0.0	0.0	0.0	0.1	0.0	0.0	223.6
5	27/10 to 10/11	56_70	-	-	-	-	-	-	-	-
6	10/11 to 24/11	70_84	0.0	0.0	0.6	0.8	0.5	0.4	0.4	94.3
7	24/11 to 08/12	84_98	0.0	0.0	0.2	0.0	0.7	0.2	0.3	173.2
8	08/12 to 22/12	98_112	-	-	-	-	-	-	-	-
9	22/12 to 05/01	112_126	0.0	0.0	0.7	1.8	0.1	0.5	0.8	149.6
10	05/01 to 19/01	126_140	0.0	0.0	0.1	0.3	0.0	0.1	0.1	138.3
11	19/01 to 02/02	140_154	0.0	0.0	1.4	1.4	0.1	0.6	0.7	125.6
12	02/02 to 16/02	154_168	0.0	0.0	0.4	0.9	0.0	0.3	0.4	152.7
13	16/02 to 01/03	168_182	3.0	0.5	1.1	1.3	0.0	1.2	1.1	96.0
14	01/03 to 15/03	182_196	0.0	0.0	0.6	1.5	0.0	0.4	0.7	155.1
15	15/03 to 29/03	196_210	-	-	-	-	-	-	-	-
16	29/03 to 12/04	210_224	0.6	0.2	0.6	0.0	0.0	0.3	0.3	110.6
17	12/04 to 26/04	224_238	0.0	0.0	0.1	0.3	0.0	0.1	0.1	158.8
18	26/04 to 10/05	238_252	0.0	0.0	0.1	0.2	0.0	0.1	0.1	142.6
19	10/05 to 24/05	252_266	0.0	0.0	0.0	0.0	0.0	0.0	0.0	223.6
20	24/05 to 07/06	266_280	0.0	0.0	2.2	1.9	0.0	0.8	1.1	136.6
21	07/06 to 21/06	280_294	-	-	-	-	-	-	-	-
22	21/06 to 05/07	294_308	-	-	-	-	-	-	-	-
23	05/07 to 19/07	308_322	0.0	0.0	0.2	0.1	0.0	0.1	0.1	127.3
24	19/07 to 02/08	322_336	0.0	0.0	0.0	0.0	0.0	0.0	0.0	156.5
25	02/08 to 16/08	336_350	-	-	-	-	-	-	-	-
26	16/08 to 30/08	350_364	1.5	0.2	0.0	0.0	0.0	0.3	0.7	189.9
Sum	01/09 to 30/08	0_364	5,1	1,0	8,7	11,1	1,6	5,5	4,4	80,3

3.6. Water balances

Table 7 shows all water balance components in a joint way. The historic average of annual rainfall in the city of Piracicaba is 1,275 mm, which shows that this year (Sept.2003/Sept.2004) was slightly more rainy than normal. The irrigation in this region is not necessary for the majority of the perennial crops, such as coffee.

Table 7. Average values of rainfall ($\overline{P}$), irrigation ($\overline{I}$), soil water storage changes ($\overline{\Delta S}$), runoff ($\overline{RO}$), drainage ($\overline{Q_L}$), actual evapotranspiration ($\overline{ETa}$), and potential evapotranspiration ($\mathrm{ET}m$), for all analyzed periods.

Balance	**Period**	**DAB**	$\overline{P}$ **(mm)**	$\overline{I}$ **(mm)**	$\overline{S_i}$ **(mm)**	$\overline{\Delta S}$ **(mm)**	$\overline{RO}$ **(mm)**	$\overline{Q_L}$ **(mm)**	$\overline{ETa}$ **(mm)**	$\overline{ETm}$ **(mm)**
1	01/09 to 15/09	0_14	4.1	34.2	245.2	12.2	0.0	0.0	-26.1	-50.1
2	15/09 to 29/09	14_28	5.8	0.0	257.4	-6.1	0.0	0.0	-11.9	-61.2
3	29/09 to 13/10	28_42	77.8	0.0	251.3	26.6	-0.2	0.0	-50.9	-58.9
4	13/10 to 27/10	42_56	17.9	0.0	277.9	-6.9	0.0	0.0	-24.8	-71.5
5	27/10 to 10/11	56_70	25.3	0.0	271.0	-7.8	0.0	0.0	-33.1	-33.1
6	10/11 to 24/11	70_84	75.1	0.0	263.3	12.3	-0.4	0.0	-62.3	-62.3
7	24/11 to 08/12	84_98	89.7	0.0	275.6	17.5	-0.2	0.0	-72.0	-72.0
8	08/12 to 22/12	98_112	49.3	0.0	293.1	-8.2	0.0	0.0	-57.5	-57.5
9	22/12 to 05/01	112_126	85.6	0.0	284.9	17.0	-0.5	0.0	-68.1	-68.1
10	05/01 to 19/01	126_140	50.6	0.0	301.9	-1.7	-0.1	0.0	-52.2	-52.2
11	19/01 to 02/02	140_154	167.7	0.0	300.2	69.8	-0.6	-54.4	-42.9	-42.9
12	02/02 to 16/02	154_168	69.8	0.0	369.9	-26.0	-0.3	0.0	-95.5	-95.5
13	16/02 to 01/03	168_182	152.9	0.0	344.0	21.1	-1.2	-79.4	-51.2	-51.2
14	01/03 to 15/03	182_196	73.1	0.0	365.1	-16.6	-0.4	0.0	-89.3	-89.3
15	15/03 to 29/03	196_210	14.0	0.0	348.5	-48.4	0.0	0.0	-62.4	-62.4
16	29/03 to 12/04	210_224	65.2	0.0	300.1	0.7	-0.3	0.0	-64.2	-64.2
17	12/04 to 26/04	224_238	52.3	0.0	300.8	0.5	-0.1	0.0	-51.7	-51.7
18	26/04 to 10/05	238_252	23.2	0.0	301.3	-6.4	-0.1	0.0	-29.6	-29.6
19	10/05 to 24/05	252_266	25.5	0.0	294.9	-0.1	0.0	0.0	-25.6	-25.6
20	24/05 to 07/06	266_280	101.5	0.0	294.8	53.8	-0.8	-21.3	-25.6	-25.6
21	07/06 to 21/06	280_294	7.2	0.0	348.7	-12.4	0.0	0.0	-19.6	-19.6
22	21/06 to 05/07	294_308	1.9	0.0	336.2	-20.0	0.0	0.0	-21.9	-21.9
23	05/07 to 19/07	308_322	32.7	0.0	316.2	26.0	-0.1	0.0	-6.6	-30.2
24	19/07 to 02/08	322_336	44.6	0.0	342.2	-12.9	0.0	-18.5	-39.0	-39.0
25	02/08 to 16/08	336_350	0.0	0.0	329.3	-11.4	0.0	0.0	-11.4	-49.3
26	16/08 to 30/08	350_364	0.0	37.5	317.8	-8.9	-0.4	0.0	-46.1	-51.0
Sum	01/09 to 30/08	0_364	1312.8	71.6	7931.6	63.7	-5.5	-173.6	-1141.7	-1336.1

The amount of irrigation water applied (71.6 mm) was only for preventing blooming to be damaged during water stress periods. Considering water inputs (P+I), it is verified that RO represents only 0.4% of the balance, which means that this component was insignificant under the experimental conditions evaluated in this study. Figure 1 shows a tendency of increasing RO as a function of increasing P. This fact is expected, but is very hard to be forecasted once RO depends more on rain intensity than on the total amount of water. It is also influenced by $S_L(t_i)$, which when low favours water infiltration.

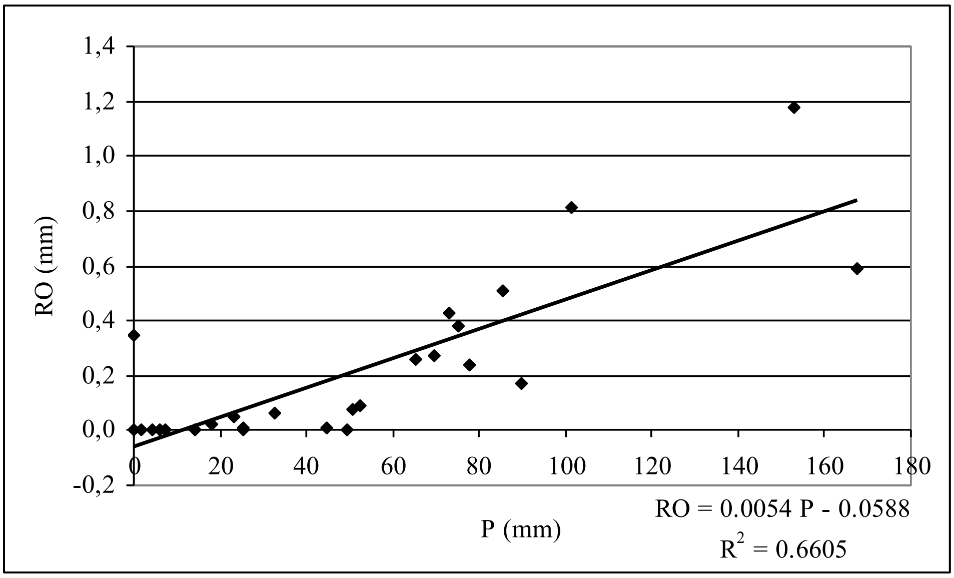

Figure 1. Variations in the runoff, RO (mm), as a function of the rainfall, P (mm).

The drainage below the depth z =1.0 m was 12.5% of the balance, which can be more significant in wetter years. In terms of N leaching, a reflex of drainage, it can be concluded that the coffee fertilization and its splitting were adequate in relation to the water balance components.

As the annual variation of ΔS should theoretically, be small over long periods such as a year (-5.5 mm in our case), the remaining of the water balance is ER, representing 82.5%. Under an ideal situation, in which RO and Q_L are null, ER would represent 100% of (P+I), that is, ER = (P+I). Such condition almost happened over the studied year.

Figure 2 shows the distribution of rainfall and of evapotranspiration along the year (Sept.2003/Sept.2004). In general, the rainfall was well distributed, except for the unsual high rainfall rate during June and July (balances 20 to 24), which are generally drier months in the region. This exception guaranteed a good development of the crop. The end of the dry seasons, represented by balances 1 and 2; 25 and 26, demanded irrigation. The highest rainfall occurred during the balances 11 and 13, and, as a consequence, the drainage (Q_L) was 12.5% of (P+I).

The actual evapotranspiration got closer to the maximum almost along the whole year, except for the dry periods (balances 1, 2, 4, 23, 25, and 26). During these periods, the coffee plants lost part of their leaves because the soil hydraulic conductivity was too low, defining a water flux to the plant root system that does not attend the atmospheric demand.

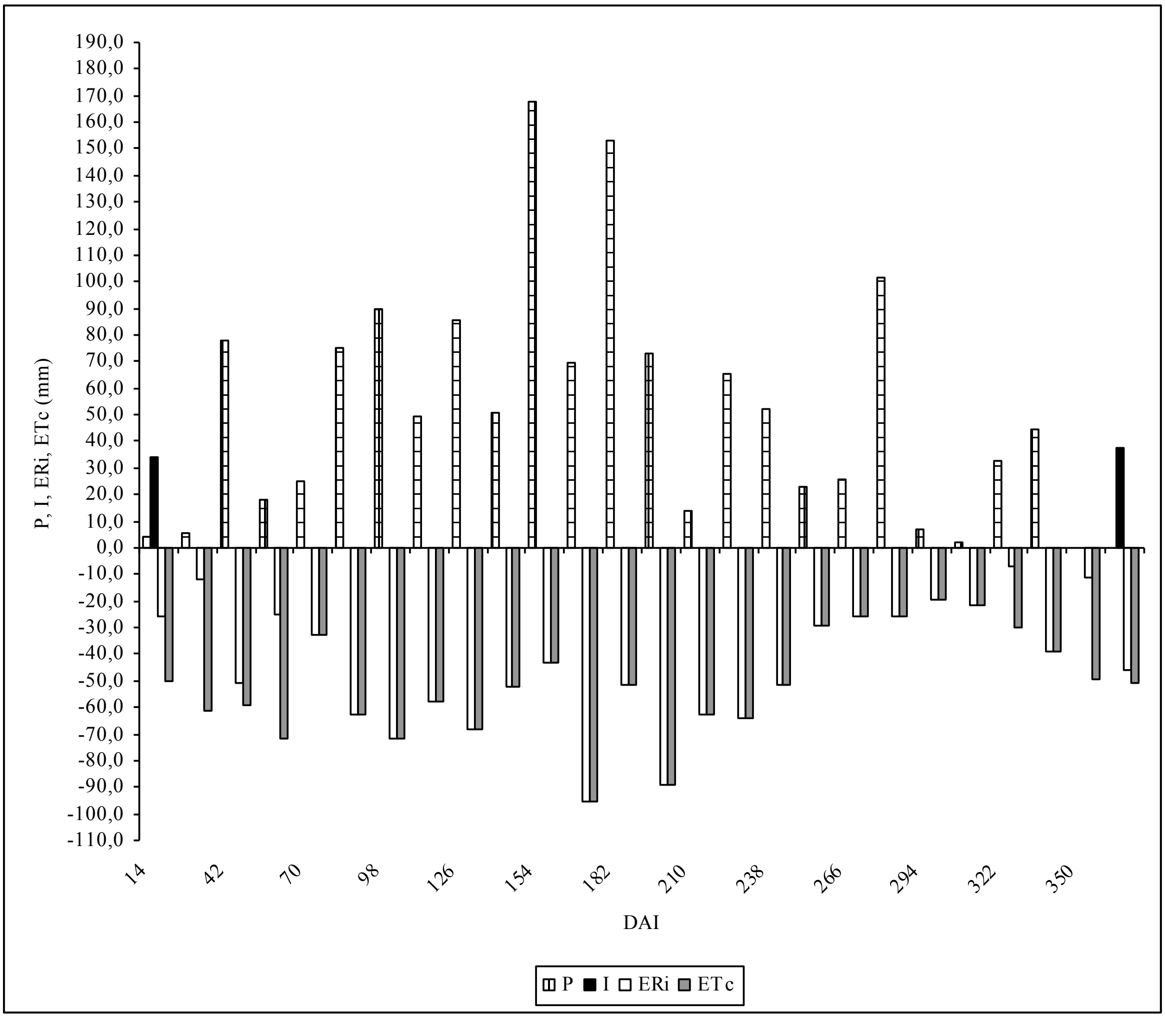

Figure 2. Variations in the rainfall (P), irrigation (I), actual evapotranspiration (ERi), and potential evapotranspiration (ETc), in mm.

4. Concluding Remarks

1. Rainfall is generally measured only at one point and, in many cases one takes the value of the nearest meteorological station. We verified that in experimental areas having obstacles nearby which affect the dynamics of the wind and, consequently, of the rainfall, the measurement of the rainfall

should be made with an adequate number of replicates. In our case, an area of 0.2 ha, with trees, silo, and warehouse located within 100 m of distance, 5 rain-gauges apart from each other by 15 to 100 m, presented CVs up to 17.8%;

2. Irrigation can introduce great variability in water balance calculations when not well controlled, due to operational problems and wind drift;

3. The atmospheric demand of the coffee crop, expressed by its actual evapotranspiration, was 1141.7 mm per year. It was not affected by the parameters that characterize the stadia of growth and development of the crop. Its estimation through water balance calculations is not recommended due to error propagation. Alternative aerodynamic methods are better choices;

4. The soil in question presents a maximum capacity of soil water storage of the order of 125 mm, which represents a backup of water for 25 days, without considering the restrictions on water flux to the roots in drier periods and considering an average demand of 5 mm/day. In this year the rainfall was near to the long term average, and was enough to meet the atmospheric demand of the crop, with restrictions in the period of dry and cold winter, favorable for blossoming. Soils with smaller storage capacity are likely to cause water supply problems and also permit larger values of internal drainage and, consequently, leaching. Soil water storage, although measured carefully, was the component that introduced most variability and error propagation in water balances;

5. The planting of coffee in areas with slopes has to be made in such a way to provide good water infiltration, minimizing runoff losses and the erosion process. Planting made in furrows along contour-lines, reduced considerably the runoff and the erosion was nil. In our case, with an average slope of 10%, the value runoff was very small, of the order from 1.7% in total of the rainfall. As expected, a positive relation between the runoff and the rainfall was observed.

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