Influence of Soil Water Retention Properties on Hydrological Cycle and Water Budgeting Module Simulation

Hamid ČUSTOVIĆ (✉)
Ognjen ŽUROVEC

Summary

The complexity of water budgeting module as shown in this paper is represented in phases. By experimental measurement of precipitation and lysimetric measurement of percolation runoff the first phase establishes monthly and annual soil-water budgets of skeletal and clayey soils, and hence the influence of soil water-retention potential on hydrologic cycle and water budget over a four year period in the area of Mostar.

Then, a soil-water budget model is simulated in a simplified procedure in order to determine the corresponding soil productive water reserve (R) for given soils. In this way, depending on R values, the output parameters of the simulated model may produce different results in: calculated surplus or percolation runoff, real evapotranspiration (RET) and water deficit.

The lysimetric measuring of the water input and output in skeletal and clayey soils determined significant differences in the water budgets of these, by physical properties, divergent soils. Such correlations indicate that there is a realistic possibility of computing new, relatively reliable and pragmatically significant agro-hydrological parameters using measured precipitation and calculated PET.

Also, this paper addresses a correlative analysis between the apple and maize ET on one side, and evaporation measured by Piche and by Class A, as well as PET calculated by Thornthwaite, Turc and Penman, on the other side. The results show a reliable reaction between ET of apple and maize with E by Piche, while the same relation is even more reliable with Class A. Other methods in this correlative analysis are less reliable.

Key words

hydrological cycle, soil water budget, ET, PET, lysimeter

University of Sarajevo, Faculty of Agriculture and Food Science,
Zmaja od Bosne 8, 71000 Sarajevo, Bosnia & Herzegovina
✉ e-mail: custovic.hamid@gmail.com

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Introduction

Ever since the first civilizations to the modern time, floods, droughts and water surpluses and deficiencies were continuous limitation factors to a stable agricultural production. Hence, the agricultural production has always been subject of large oscillations. On the other hand, man has always tried to deal with such unfavorable influences, to mitigate or even eliminate them completely. Along with the development of knowledge and techniques, they devised means and measures for a more or less successful way of solving these problems.

In order to have a reliable and stable agricultural production it is necessary to place the water regime under control and master the methods of water programming and management. The optimal soil water regime is the shortest and most reliable way of stabilizing the agricultural production.

The soils of Herzegovinian karst are the object of study among our many researchers (Hakl, 2004; Vlahinić, 2002). Such interest has recently become even bigger, due to multipurpose utilization of the karstic water resources and related reasonable use of land.

However, a modern approach to the organization of agricultural production worldwide, as well as in our country, is primarily focused on resolving the issues of the water/physical properties of the soil and their dynamics under the given agrohydrological conditions. These researches are aimed at studying the dynamics of hydrological processes and shedding some new light on the certain aspects of the soil hydrology. In this sense, a huge contribution was made by Thornthwaite (1948), by introducing the terms of potential evapotranspiration (PET) and real evapotranspiration (RET).

Roblin (1958) was the first to evaluate the SET/PET ratio (simulated/potential evapotranspiration) in programmed yield of agricultural crops, and develop a diagram. Clothier (1989) stated that divergent perceptions in agro-hydrology are a consequence of poor cooperation of scattered scientific disciplines lacking joint effort in studying the limiting role of water in development of agricultural crops.

The obtained research results could have significance from both scientific and pragmatic point of view. In the area of Mostar, there has been a long and continued practice of measuring and recording the meteorological and agro-hydrological parameters, which enables the calculation of trends and simulation of modules of some of the most relevant agro-hydrological parameters on skeletal and clayey soils.

Materials and methods

The experimental measurement of precipitation (P) and lysimetric measurement of percolation runoff (Om) are carried out in the first phase in order to determine monthly and annual soil-water budget of the skeletal and clayey soil and hence the impacts of the soil's water-retention potential on hydrological cycle and water budget over a four year period. The pedophysical properties of examined soils are shown in Figure 1.

In the second phase, a module of soil-water budget is simulated in a simplified procedure, using the following three input parameters:

– Monthly precipitation (P)
– Monthly potential evapotranspiration calculated by Thornthwaite (PET)
– Reserves of easily accessible soil water in series of 50, 100, 150, 200, 250 and 300 mm, in order to determine a corresponding soil productive water reserve (R) for a given soil.

In this way, depending on R, the outcome parameters of the simulated module reach different values of:

– calculated surplus or percolation runoff (Oc)
– real ET (RET)
– water deficit (D)

The above stated analysis depends primarily on the obtained results of the calculated surplus or percolation runoff in relation to R.

In the final phase of the procedure, a correlation analysis of the lysimetric measured percolation runoff (Om) and calculated surplus (Oc) for various R is conducted to determine the following:

– reliability of the module, and
– values of R at which the measured (Om) and calculated (Oc) runoff in skeletal and clayey soil are the best correlated.

The lysimetric research method, being the most reliable in agro-hydrology, was used in the field. The installed lysimeters have the following specifications: cubage of 1.7 m^3, diameter of 1.2 m and depth of 1.5 m. The total surface area of the lysimeter is 1.13 m^2 . The lysimeters are connected to the measuring instruments for drainage runoff control. They are stationed around the control shaft that contains the compensation chambers for each lysimeter and lysimeter sub-irrigation system based on water re-circulation principle.

The lysimeters were studied for maximum water uptake on ET (ET=P+Ir-V) under the conditions of unlimited water supply through irrigation, as well as for reduced water uptake in grass mixtures without irrigation.

The object crops of the research were apples, variety Granny Smith, and maize, a hybrid of medium early ripening season. Immediately before the establishment of the plantations, all agrotechnical measures required for the stated crops were applied.

During the five-year research period, precipitation, air temperature, relative humidity, insolation and wind speed data was measured and compared with longtime series for this area: precipitation for 60 years, air temperature for 62 years, and the relative humidity, insolation and wind speed for a 16-year period of measurements on experimental checkpoint.

Average annual rainfall for the 60-year period was 1,470 mm and 1,049 mm during the research period (421 mm lower). From these data, it can be seen that the research period diverged significantly (28.64%) from the 60-year time series and distribution of rainfall per year. This may be due to stochastic character, which is typical in Mediterranean pluviometric regime, but it may be the result of decreasing trend of precipitation in this area and a hint of larger changes in hydrological regime.

Precipitation during the year has a typical Mediterranean character. The bulk of the annual precipitation occurs during the colder months of the year when it is not required by plants, while during the vegetation season there are obvious deficits.

Table 1. Measured and calculated annual runoff (mm)

Elements		Year 1	2	3	4	Average
Calculated annual runoff (Oc) depending on R	R = 50 mm	877	479	307	591	564
	R = 100 mm	810	429	257	541	509
	R = 150 mm	710	379	207	491	447
	R = 200 mm	610	329	157	441	384
	R = 250 mm	510	308	123	346	322
	R = 300 mm	410	308	73	246	259
Measured annual Runoff (Om) in soil	Skeletal	800	396	216	549	490
	Clayey	457	251	72	479	315

The annual mean air temperature during the 60-year period was 14.9 °C, and 14.5 °C during the examination period (0.4 °C lower). Temperature in the studied period diverged from the long-term average. The warmest month in 60-yeat series is July, while the warmest month in research period was August. January was the coldest month in both cases.

Measurements of relative humidity were compared with the 16-year period of measurements on the same location. Results of mean annual values are fully matching (73%).

The average annual insolation in the research period was 2271.2 hours, and 2149.3 hours for a 16-years period. This deviation is not significant.

The average wind speed in the research period (2.5 m/s) was significantly different from the previous 16-year period (1.3 m/s).

Results

Simulation of the water budgeting module

During the 4-year period, recorded percolate was higher by 55,5% in skeletal than in clayey soil. This means that over the year, clayey soil under grass and in no irrigation conditions provides around 175 mm of productive moisture more than the skeletal one. Namely, out of the mean annual precipitation of 1.032 mm, 47% went to percolate in skeletal soil, whereas only 30% in clayey soil. As for the annual precipitation input, the skeletal soil provided 53% productive moist and clayey 70%.

Additionally, differences in the outflow regime throughout the year were evident. In July, August and September, and practically in June as well, there was no outflow in either skeletal or clayey soil. This is the period of discharge of soil water reserves where precipitation is in short supply. The recovery of soil water reserves begins in October, again with significant differences in the quantity of percolate between skeletal and clayey soils.

Assuming that the R of the soil productive water vary within a wide range – 50 to 300 mm – during the four year period of research, a total of six modules of water budgeting were developed based on the measured monthly precipitation, calculated PET and hypothetical R values of 50, 100, 200, 250 and 300 mm (Table 1). Within the scope of water budgeting process, we were particularly interested in the result of the calculated monthly and annual surplus or calculated runoff (Oc) because of comparison and establishment of the correlation with the measured percolation runoff.

The comparison of annual values is very interesting. The mean four-year measured runoff in skeletal soil gets closest to the calculated runoff with R = 100 mm, and in clayey soil with R = 250 mm. A much better insight into these relations is provided by the statistical correlative analysis explained in the following procedure (phase).

Statistical correlative analysis

The statistical correlative analysis was conducted for the purpose of verification of the soil water budgeting simulation module and determination of appropriate reserve (R) with which the module could be applied in skeletal and clay soils.

For this purpose, the annual and monthly measured runoff in skeletal and clayey soils were correlated with the calculated annual and monthly runoff in accordance with previously described model for six different values of R (Table 2).

Table 2. Correlation coefficients

R Value (mm)	Correlation coefficient yearly values		Correlation coefficient monthly values	
	Skeletal	Clayey	Skeletal	Clayey
50	0.997	0.848	0.966	0.758
100	0.998	0.857	0.949	0.777
150	0.999	0.884	0.901	0.829
200	0.996	0.914	0.799	0.868
250	0.980	0.875	0.628	0.881
300	0.881	0.755	0.492	0.814

Very high correlation coefficient between the researched parameters indicates the module's reliability.

With regard to the selection of appropriate R, it ranges from 50 and 150 mm, i.e. 100 mm on average, for skeletal soils, and from 200 to 250 mm for the clayey ones.

Real evapotranspiration (RET) under the irrigation conditions (May - September)

The average water uptake during five months (May – September) in a two-year period reached 552 mm in apple and 941 mm in maize.

However, depending on energy available in the atmosphere, the uptake varies from year to year. In 1989, it amounted to 532 mm in apple (monthly max – 142, and min – 49 mm), while in 1990, it reached 573 mm (monthly max - 134, and min - 85 mm) (Table 3).

The energy available in atmosphere on one, and developmental stage of the plant on the other hand, have a huge impact

Table 3. Real evapotranspiration (RET) in mm

Month	Apple		Maize	
	1989	1990	1989	1990
V	49	85	48	90
VI	106	106	118	159
VII	142	134	239	448
VIII	128	129	261	275
IX	107	119	135	109
Total V-IX	532	573	801	1.081
2-year average	552		941	

Table 4. Correlation coefficients

X – PET by:	Thornthwaite	Turc	Penman
y – ET of apple	0.725	0.524	0.435
y – ET of maize	0.736	0.803	0.768

on water uptake dynamics in the majority of plant species, to include apple.

The above stated data indicates that the water uptake increases on ET in the second year of experiment and second year in age (1990) in apple amounted to only 8% (relative to 1989, i.e. first year), although due to age factor this increase was expected to be higher. The reason lies in pest infection (*Rhynchites caeruleus*), which attenuated the vegetative development and growth of apple in the second year, causing the lack of expected increase of water uptake on ET.

In maize, the recorded water uptake on ET was increased in 1990 by 35% (Table 3). In 1989 it amounted to 801 mm (monthly max was 261 mm, and monthly min 48 mm), while in 1990, it reached 1091 mm (monthly max was 448 mm, and monthly min 90 mm). The average for both research years was 941 mm.

The increased water uptake in 1990 was probably the result of more energy available in the atmosphere that year.

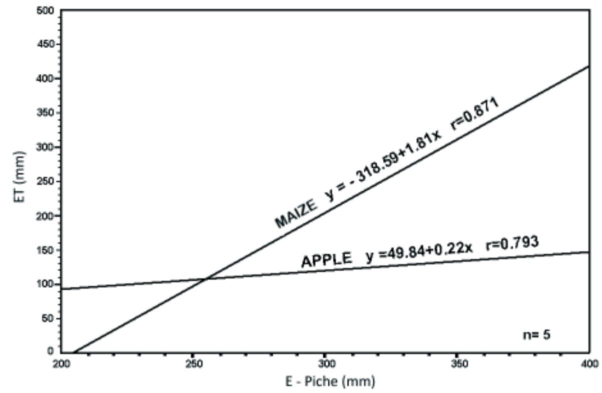
Correlative analysis of monthly RET, E and PET values

The computer programs for water budgeting (SPAW, WIF) that are used to program irrigation, drainage outflow, water quality control and plant water stress control, require data on real evapotranspiration (RET) for any subject crops, as one of the key input parameters. Since the measured RET data is rarely available, it could be obtained indirectly, by establishing a reliable correlation between the crop's RET on one, and measured E or calculated PET on the other side.

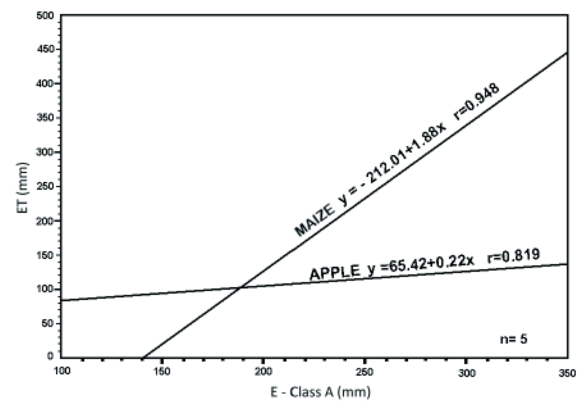
This example represents a correlative analysis between apple and maize ET and evaporation measured by Piche, or Thornthwaite, Turc, Penman.

a) Correlation between apple and maize PET and E by Piche and Class A

The statistical analysis with regression equations and correlation coefficients supports a rather reliable relation between apple (r =0,793) and maize (r =0,871) RET with E by Piche during the vegetation period in 1990. (Graph 1)



Graph 1. Correlation between apple and maize monthly ET (y) and E Piche (x)



Graph 2. Correlation between apple and maize monthly ET (y) and E Class A (x)

The situation is similar in case of correlation between apple (r = 0.819) and maize (r = 0.948) RET and E by Class A (Graph 2). This relation is somewhat more reliable in case of apple and maize RET and E by Class A, than in case of E by Piche.

This is probably why a large number of countries use the Class A evaporation as a reference data for determining RET in various crops. Also, based on Class A evaporation, a special method for calculation of PET (FAO Irrigation and Drainage paper, No 24 and 33) has been developed.

However, it has to be noted that the one-year measuring results can not be considered as referential (the measuring of evaporation was conducted only in 1990), therefore, their verification over a longer period of time is required. For this reason, such results could be considered as preliminary, though generally, not much time is spent on pragmatic solution to the problems as the research network at local level is much richer.

b) Correlation between apple and maize RET and PET by Thornthwaite, Turc and Penman

The statistical analysis with regression equations and correlation between apple and maize RET on one, and PET calculated by Thornthwaite, Turc and Penman, encompasses the two-year results for the period of May-September (n = 10), and provides the following correlation coefficients (Table 4)

It shows that the Turc and Penman's calculation method can not be reliably used in apple (r=0.524 and r=0.435), whereas the Thornthwaite's method is slightly more reliable. In maize, the Turc's method is more reliable (r=0.803) than Penman's (r=0.796) and Thornthwaite's (r =736).

In using the measured E and calculated PET data as referential for determining the RET, preference should yet be given to the data on E by Class A for determining RET due to the strongest correlation ties identified.

Conclusion

Assuming that the soil productive water reserves (R) vary within a wide range – 50 to 300 mm – during the four year period of research, a total of six water budgeting modules were developed based on the measured monthly precipitation, calculated PET and hypothetical R values of 50, 100, 200, 250 and 300 mm. Within the scope of water budgeting process, we were particularly interested in the result of the calculated monthly and annual surplus or calculated runoff (Oc) in order to be able to make a comparison and establish a correlation with the measured percolation runoff.

The comparison of annual values shows that the mean four-year measured runoff in skeletal soil gets closest to the calculated runoff with R = 100 mm, and in clay with R = 250 mm.

A much better insight into these relations is provided by the statistical correlative analysis made for the purpose of verifying the water budgeting simulation module and determining appropriate reserves (R) that would allow the module's application skeletal and clayey soils. The correlation was established between the annual and monthly measured runoff in skeletal and clayey soil on one, and calculated annual monthly and annual runoff based on previously described module for six different values of R on the other side.

The very high correlation coefficient between the researched parameters indicates the module's reliability.

The lysimetric measuring of the water input and output in skeletal and clayey soils determined significant differences in the water budgets of these, by physical properties, divergent soils.

Such correlations indicate that there is a realistic possibility of computing new, relatively reliable and pragmatically significant agro-hydrological parameters (such as potential runoff, water deficit, RET, draught coefficient or water stress i.e. RET/PET), using measured precipitation and calculated PET.

Based on the correlation established between the apple and maize ET on one, and evaporation measured by Piche and by Thornthwaite, Turc, Penman on the other side, we could conclude the following:

- The statistical analysis with regression equations and correlation coefficients shows a rather reliable connection between the RET of apple (r =0.793) and maize (r =0.871) and E by Piche during the vegetation period in 1990. It is similar with the RET of apple (r=0.819) and maize (r=0.948) and E by Class.
- The statistical analysis with regression equations and correlations between the RET of apple and maize on one, and PET calculated by Thornthwaite, Turc and Penman on the other side, shows that the Turc and Penman's calculation method cannot be reliably used in apple (r=0.524 and r=0.435), whereas the Thornthwaite's method in apple is somewhat more reliable. However, in case of maize, the Turc's method (r=0.803) is more reliable than the Penman's (r=0.796) and Thornthwaite's (r=0.736).

In using the measured E and calculated PET data as referential for determining the RET, preference should yet be given to the data on E by Class A for determining RET, due to the strongest correlation ties identified.

With regard to the fact that the majority of soils in the region of Herzegovina fall into the R = 100 mm category, it is possible to apply a retrospective extension of the calculated procedure on a long-lasting time series. By doing so, it would be possible to determine the long-term tendencies and frequency of the major agro-hydrological parameters, as it was done in this paper for the region of Mostar. This could also serve as a basis for programming the selection of crops that are best suited to the identified modules of soil water regime without irrigation.

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