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IrrigTool—A New Tool for Determining the Irrigation Rate Based on Evapotranspiration Estimated by the Thornthwaite Equation

Cristian Ștefan Dumitriu [1], Alina Bărbulescu [2,*] and Carmen Elena Maftei [2]

[1] S.C. Utilnavorep S.A., 55 Aurel Vlaicu Av., 900055 Constanța, Romania; cristian.dumitriu@unitbv.ro
[2] Faculty of Civil Engineering, Transilvania University of Brașov, 5, Turnului Str., 900152 Brașov, Romania; cemaftei@gmail.com
* Correspondence: alina.barbulescu@unitbv.ro

Abstract: In the context of climate change, irrigation has become a must for ensuring crop production because in some regions, the drought episodes became more frequent. The decision to efficiently allocate water resources should be made quickly, based on tools that provide correct information with a low computational effort. Therefore, we propose a new user-friendly tool—IrrigTool—for assessing the irrigation rate considering the precipitation, temperature, evapotranspiration, soil type, and crop. IrrigTool implements the Thornthwaite equations and can be used to identify weakness due to drought stress and as an educational tool. Apart from the computation, it provides a graphical representation of the results and possible comparisons of the output for two locations. The application is built in Microsoft Excel for graphics and Visual Basic VBA. The user does not have programming knowledge to use it. Data on monthly precipitation and temperature data must be introduced in the specified fields, and after pressing the run button, the results are automatically displayed. The article exemplifies the functioning on data series from Romania's Dobrogea region.

Keywords: evapotranspiration; irrigation; soil water reserve; water balance

1. Introduction

Water scarcity is one of the world's most critical issues since water resources are not uniformly distributed and are affected by pollution. Moreover, people from some regions have no access to fresh water. Industrial activities, intensive chemical fertilizers utilization, vehicle exhaust, acidic rain, and climate change are among the most critical threats to groundwater quality [1,2]. The water quality for agricultural use is questionable in many situations, while in others, the water composition is not appropriate for such use [3]. Thus, water availability has become a restrictive factor for irrigation in different world regions [4].

In climate change conditions, this issue becomes more acute [5]. Since a population of about 7 billion people must be fed, an increasing concern for ensuring food necessities has manifested. Scientists and professionals should cooperate to find new approaches to ensure food production [6]. Different solutions have been proposed, each based on the particular climate of the region of interest. Rational irrigation, influenced by climate, crop, and soil type, aiming at ensuring the humidity necessary for plants' development and minimizing water consumption, is one of them [7].

While the climate influences irrigation necessity, it seems that, in its turn, irrigation impacts the climate of the regions where it is applied [8–10].

Efficient irrigation should consider the new technology and water management practices that may increase the performance of the available irrigation systems [11,12].

Different authors presented the procedure of "irrigation interval" scheduling [13] available only for particular regions. For example, the Michiana Irrigation Scheduler program schedules irrigation for some crops using the Stress Day Index and provides the

estimated final yield throughout the season as the soil becomes too dry. The KanSched benefit by a network of weather stations and evapotranspiration (*ETRM*) is found on the Internet, but data must be input by hand. The Computerized Irrigation Scheduling by the Checkbook method (North Dakota State University) uses an earlier bulletin on checkbook irrigation scheduling. The Cropflex 2000 developed by the Colorado State University aims at managing irrigation and fertility. The Woodruff Chart maker developed by the University of Missouri uses the historical hydro-meteorological data for drawing an accumulative water-use curve for crops, emergence date, and weather. The curve is a graphical tool for scheduling the irrigations. Unfortunately, these software are of particular use for some USA regions only.

Water-requirement tables have been built by other scientists [14,15] based on the FAO documents [16,17]. Different software have been proposed to compute the evapotranspiration, an essential component of the water balance equation, mostly based on the Penman–Monteith equation [18,19], which is the official method adopted by FAO. CROPWAT 8.0 [20], WTRBLN [21], EVAP [22], and Excel worksheets have been proposed over time for water-balance calculation based on the Thornthwaite–Mather methodology [23] or estimating the *ETRM* by the Hamon equation [24].

WTRBLN [21] that computes the water balance has its initial version in Basic 3.0, and the new one in MATLAB needs a license to be used as well as computational skills. The Excel 2000 worksheet announced by Armiraglio et al. [23] is available on request, and that of Mammoliti et al. [25] computes only the water balance. EVAP [22] is a FORTRAN program that implements the Thornthwaite equation for the ETRM computation similar to [20,21,23] but not the irrigation rate.

Related studies using remote sensing (RS) are those of Droogers et al. [26], Olivera-Guerra et al. [27], Brocca et al. [28], Bretreger et al. [29], and Foster et al. [30].

Droogers et al. [26] proposed an irrigation scheme based on a two-step modeling approach. The remote-sensing *ETRM* was used for optimizing two parameters of the SWAP model, and then, a forward–backward algorithm was applied to assess the accuracy of remotely sensed actual *ETRM*. Olivera-Guerra et al. [27] proposed a new methodology to estimate the timing and the irrigation rate based on the Landsat-7/8 data in the following stages: deriving the crop water stress coefficient from the Landsat land surface temperature, estimating the daily root zone soil moisture, retrieving irrigation at the Landsat pixel scale, and aggregating pixel-scale irrigation estimates at the crop field scale.

Through the inversion of the soil-water balance equation and by using satellite soil moisture products as input, the amount of water entering into the soil and hence irrigation is determined by Brocca et al. [28]. The study of Bretreger et al. [29] utilized the Landsat satellites (5–8) for monitoring the crop situation based on the vegetation index for assessing crop development through a crop coefficient. Soil parameters were provided by the digital soil maps and in situ observations. The results were in concordance with the recorded irrigation time series. Foster et al. [30] presented an analysis of the relative accuracy of different satellite-based irrigation water-use monitoring approaches, with evidence of large uncertainties when water-use estimates are validated against in situ irrigation data at both the field and regional scale.

In this context, this study introduces a new tool—IrrigTool—aiming to optimize the water supply necessary for crop growth based on the average monthly temperatures and precipitation, the soil characteristics, and the type of agricultural crop. It uses the Thornthwaite equation for the *ETRM* computation. This tool can be utilized for learning and practical purposes. It is can also be used without deep knowledge of computer science.

2. Methodology

This section contains the basic formulas employed for the implementation purposes necessary to understand the implementation.

The irrigation rate (*M*) is the water quantity used to irrigate the surface of 1 ha cultivated with a specific type of plant. Hence, it represents the total water quantity that

must be applied to a crop during and outside the vegetation period to fill the soil moisture deficit up to the value of the potential evapotranspiration [31].

The water application rate (*m*) is the quantity of water necessary per 1 ha of the crop during a unique watering operation. Therefore,

$$M = \sum m \tag{1}$$

and the watering number is

$$n = M/m. \tag{2}$$

The watering number is rounded up to the closest natural number, and the irrigation rate will be corrected accordingly.

The first element that must be considered for computing the irrigation rate is the water loss by evapotranspiration. The monthly water consumption by the plants' evapotranspiration and evaporation from the soil surface, denoted in the following by ETRM (m^3/ha), is computed here by the Thornthwaite equations, with a correction that depends on the crop and geographical zone.

For a month *j*, *ETRM* is calculated by [32]:

$$ETRM_j = 160 \times \left(10t_j/\mathrm{I}\right)^a \times K_1 \times K_p \tag{3}$$

where:

t_j—the medium temperature of the *j*-th month, *j* = 1, ... , 12.
I—the annual thermic index:

$$I = \sum_{j=1}^{12} \left(\frac{t_j}{5}\right)^{1.514} \tag{4}$$

$$a = 6.75 \times 10^{-7} \times I^3 - 7.71 \times 10^{-5} \times I^2 + 1.792 \times 10^{-2} \times I + 0.49239, \tag{5}$$

where K_1—a coefficient specific to each latitude,

K_p—a coefficient that depends on the crop type.

The second element to be estimated is the water soil storage (m^3/ha).

Outside the vegetation period, the depth taken into account for computing the water available to the plant is the maximum thickness of the storage layer from which the plant can utilize the water (*H*). *H* = 1.5 m for deep soils, *H* = the real soil depth for soils with short profiles, and *H* = the specific depth for soils with heavy and compacted argillic layers [32].

Outside the vegetation period, the soil water reserve varies in the interval [$R_{min,\,H}$, $R_{max,\,H}$], where [32]:

$$R_{min,H} = 100 \times H \times DA_H \times C_{0,H}, \tag{6}$$

$$R_{max,\,H} = 100 \times H \times DA_H \times C_{c,H}, \tag{7}$$

- $R_{min,H}$ (m^3/ha)—the minimum water reserve in the soil, corresponding to the wilting point, at the depth *H*,
- $R_{max,H}$ (m^3/ha)—the maximum water reserve in the soil, corresponding to the water field capacity, at the depth *H*,
- DA_H (t/m^3)—the soil bulk density corresponding to the depth *H*,
- $C_{c,H}$ (%)—the water field capacity corresponding to the depth *H*,
- $C_{0,H}$ (%)—the wilting coefficient corresponding to the depth *H*.

During the vegetation period, the water soil storage computation considers the depth of the active layer (where the principal mass of roots is developed at the maturity stage) *h* and the soil type. Therefore, for this period, the maximum and minimum water reserve in soil $R_{max,h}$ ($R_{min,h}$) are given by [32,33]:

$$R_{max,h} = 100 \times h \times DA_h \times C_{c,h} \left[\mathrm{m}^3/\mathrm{ha}\right], \tag{8}$$

$$R_{min,h} = 100 \times h \times DA_h \times P_{min,h} \left[\text{m}^3/\text{ha}\right], \tag{9}$$

with

- DA_h (t/m^3)—the soil bulk density corresponding to the depth h,
- $C_{c,h}$ (%)—the water field capacity corresponding to the depth h.
- $P_{min,h}$(%)—the minimum moisture level, defined as the limit under which the soil humidity should not decrease for ensuring normal conditions for the plant growth. It is computed at the depth h by [34]:

$$P_{min.h} = \begin{cases} C_{0,h} + 1/3(C_{c,h} - C_{0,h}), & \text{for light textural type} \\ C_{0,h} + 1/2(C_{c,h} - C_{0,h}), & \text{for medium textural type} \\ C_{0,h} + 2/3(C_{c,h} - C_{0,h}), & \text{for heavy textural type} \end{cases} \tag{10}$$

where $C_{0,h}$ (%)—the wilting coefficient, corresponding to the depth h.

$P_{min,h}$ depends on the soil texture and takes values between the field capacity and the wilting coefficient.

The water balance equation for a month is [34]:

$$R_f = R_i - ETRM + P_u - A_f \tag{11}$$

where:

$ETRM$—the monthly water consumption by the plants' evapotranspiration and evaporation from the soil surface,

P_u (m^3/ha)—the water intake from precipitation in that month,

R_i (m^3/ha)—the initial water reserve in soil at the considered depth, at the beginning of the month,

R_f (m^3/ha)—the final water reserve in soil for the considered depth at the month's end,

A_f—the groundwater supply. A_f is positive only for deep-rooted plants (alfalfa, corn, beets, soybeans, trees, etc.). Otherwise, $A_f = 0$.

In areas where irrigation is applied before sowing, the initial water reserve is taken equal to the field capacity $C_{c,H}$.

In rainy years during the vegetation period, when $P_u > ETRM + R_f - R_i$, irrigation is not necessary because the amount of rainfall completely covers the water need.

The water balance computation starts from 1st of October (October is the first month of the agricultural year). The water reserve at the end of a month j (R_{f_j}) becomes the initial water reserve for the next month ($R_{i_{j+1}}$).

From the above, it results that for the months October–March (months I–VI of the agricultural year), the water balance is calculated at H, whereas for the vegetation period (April–September), it is calculated at the depth h [34,35].

To compute the irrigation rate, the following rules should be followed:

a. The water reserve in soil must be lower than $R_{max,H}$ ($R_{max,h}$) in the cold (vegetation) season. When it is higher, the quantity that exceeds the above limits is considered lost by infiltration and cannot be used by plants;

b. In the cold period, the water reserve can decrease without limitation except for the crops subject to water provision.

c. In the vegetation period, the water reserve cannot decrease under $R_{min,h}$. If the reserve decreases under this value, watering must be applied.

If the groundwater level varies during the year, then the groundwater supply will be considered resulting from hydrological forecasts. If the groundwater level does not vary during the year, then one may use the data from [18].

The water application rate is computed by [36]:

$$m = 100 \times h \times DA_h \times (C_{c,h} - P_{min}). \tag{12}$$

The flowchart of the study is presented in Figure 1.
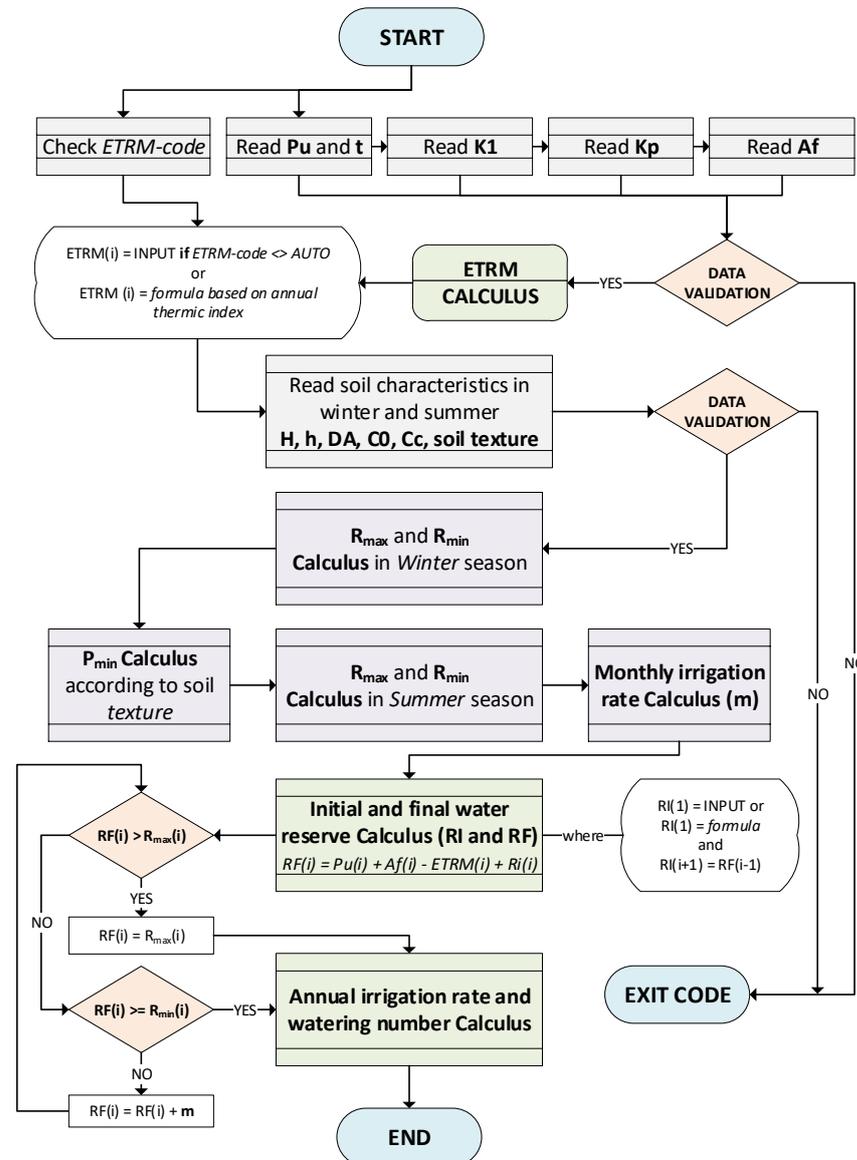
Figure 1. Flowchart (the variables are denoted in concordance with the coding).

The analysis steps (according to Figure 1) are:

(a)　Input data from the Excel files where they have been previously introduced. They are: monthly precipitation (P_u in the flowchart) and temperature series (t– in the flowchart), the series of the monthly coefficients K_1 and K_p, and the A_f series. The input data are validated by checking if the cells are filled in with numerical values. If not, the algorithm stops. Otherwise, it passes to the next step, as follows:

(b)　Read the soil characteristics, namely H, h, DA, C_0, and C_c, corresponding to h and H from the worksheets where they were previously introduced. If all the values are numerical, and none is absent, the algorithm passes to step (c). Otherwise, it stops.

(c)　Compute R_{min} and R_{max} for winter;

(d)　Compute P_{min};

(e)　Compute R_{min} and R_{max} for summer;

(f)　Compute the monthly irrigation rate;

(g)　Compute the initial and final water reserve for each month;

(h)　Compute the water application rate and the annual irrigation rate;

(i)　　Display the results and the graphical representation.

3. Data Series

The climate in Romania is continuously changing, so the drought regions are becoming more arid. The Dobrogea region (Figure 2), situated in the south-eastern part of the country, is experiencing a more extended period without precipitation followed by short periods with high rainfalls. It was shown that the mean annual temperatures were augmented by 0.8 °C after 1997, and many rivers are drying up in summer. Increasing trends are noticed for the region's maximum and minimum annual, summer, winter, and spring temperature series [37–41]. Therefore, the necessity of crop irrigation becomes more relevent than ever.
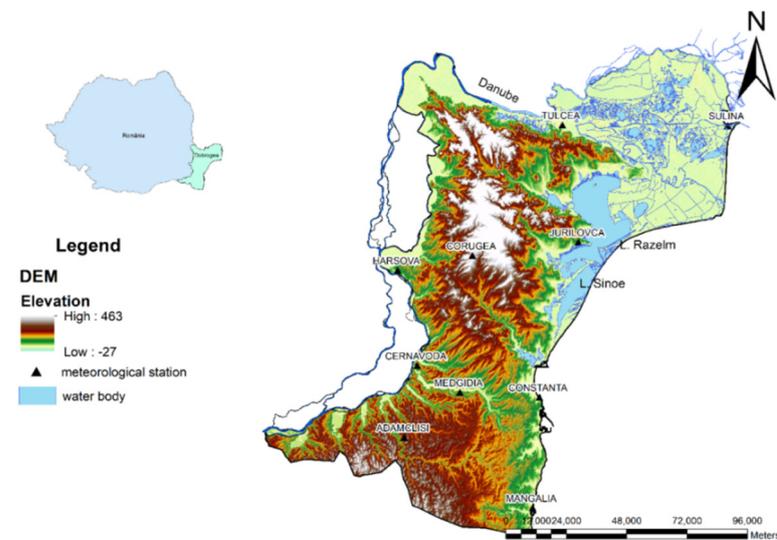
Figure 2. The map of Dobrogea [41].

The monthly average temperatures and precipitation series recorded at Constanța (CT) and Tulcea (TL) during the agricultural years 1998–2019, which were employed to exemplify the proposed tool, are presented in Figure 3. The basic statistics of these series are given in Table 1.
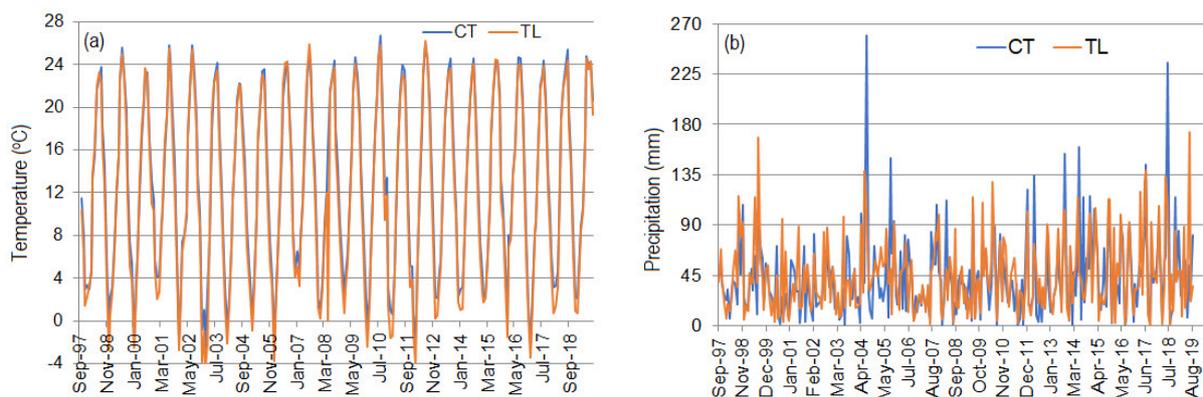
Figure 3. Monthly average (**a**) temperature and (**b**) precipitation series recorded at Constanța (CT) and Tulcea (TL).

Table 1. Basic statistics of the CT and TL monthly series used for exemplification.

Series	Max	Min	Mean	Median	Std. Dev.	Coef. of Variation	Skewness	Kurtosis
CT precipitation	259.20	0.30	43.27	36.00	36.53	0.84	1.96	6.95
TL precipitation	173.00	0.00	44.83	37.35	33.91	0.76	1.06	0.85
CT temperature	26.70	−0.20	12.83	12.60	8.17	0.64	−0.03	−1.29
TL temperature	26.20	−4.50	12.08	11.65	8.60	0.71	−0.06	−1.28

4. Implementation

The application was built in Microsoft Excel for graphics and VBA (Supplementary Materials S1 and S2) because these environments have also been employed for hydrological analysis, and the environment is easy to use [42–46].

The application's structure allows the irrigation rate calculation for two locations (S1 and S2) and the comparison of results.

The main worksheets—"Irrigation S1" (Figure 4) and "Irrigation S2"—contain the work data for each site, the numerical results obtained, and the afferent charts obtained after running the algorithm.
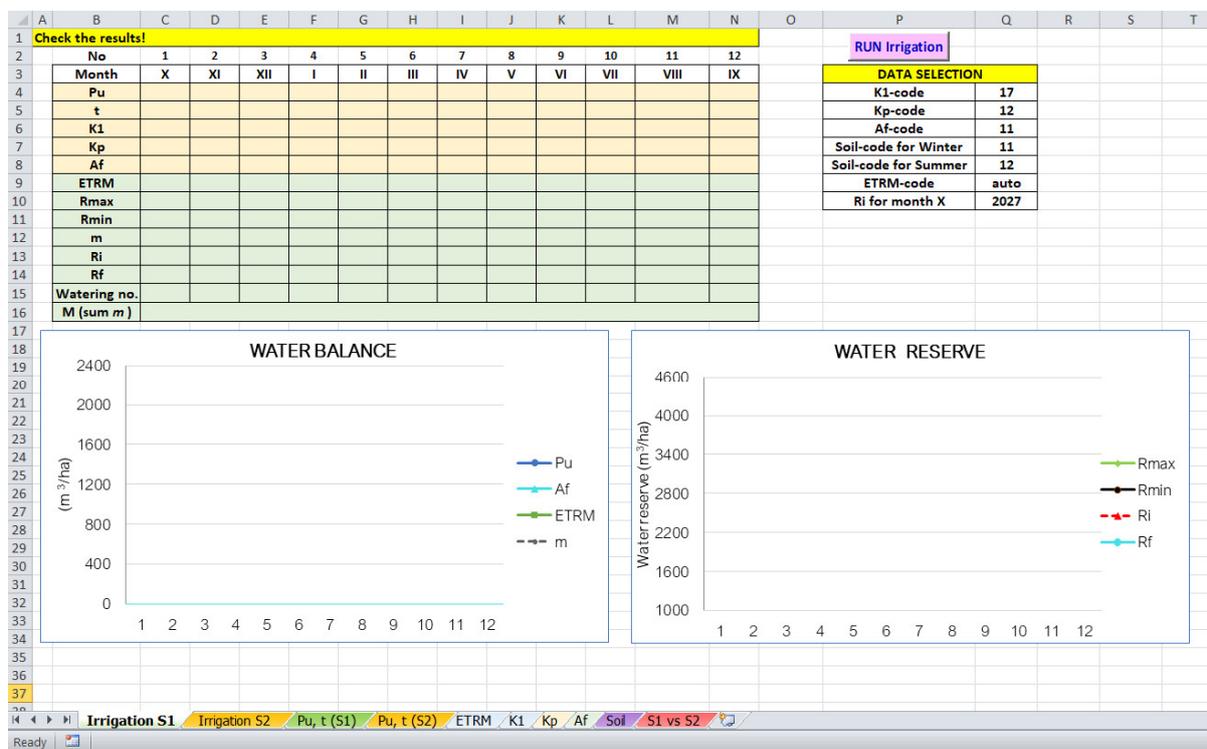
Figure 4. The "Irrigation S1" worksheet.

Before running, the input data is entered in seven worksheets ("Pu, t (S1)", "Pu, t (S2)", "ETRM", "K1", "Kp", "Af", and "Soil") that are simple and easy to populate by the user with data according to its need. They will be presented in the following section.

The software selects the values of interest through numerical codes, which correspond to the data sets entered by the user. In the "Irrigation S1" and "Irrigation S2" worksheets, the user indicates the codes (settable by him) in the table entitled "DATA SELECTION".

The user will introduce into the cells Q4–Q11 the following codes:

− in Q4—a code selected from the first column of the worksheet "K1";
− in Q5—a code selected from the first column of the worksheet "Kp";
− in Q6—a code selected from the first column of the worksheet "Af";

− in Q7—a code selected from the first column of the worksheet "Soil" corresponding to the winter season;

− in Q8—a code selected from the first column of the worksheet "Soil" corresponding to the summer season;

− in Q9—a code selected from the first column of the worksheet "ETRM" or "auto";

− in Q10—"0" or a value selected by the user.

Details will be provided in the following section.

The software takes the data corresponding to the codes from the worksheets "Pu, t (S1)" (Figure 5), "ETRM" (Figure 6), "K1" (Figure 7), "Kp" (Figure 8), "Af" (Figure 9), and "Soil" (Figure 10).

	A	B	C	D	E	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	From year...	To year...	Pu (mm)	t (°C)		22 years	Check the results!											
2	1	22	38.8	10.4		Month	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX
3			68	6.2		Pu$_{Avg}$												
4	Find Averages		40.7	1.4		t$_{Avg}$												
5			20	2.2														
6			5.8	3.4														
7			20.2	4.4														
33			3.5	18.2														
263			173	23.6														
264			22	24.3														
265			35	19.3														
266																		

Sheet1 | Irrigation S1 | Irrigation S2 | Pu, t (S1) | **Pu, t (S2)** | ETRM | K1 | Kp | Af | Soil | S1 vs S2

Figure 5. The "Pu, t (S1)" sheet.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1															
2															
3	ETRM-Code	References	Month	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX
4	11		ETRM	340	172	56	20	48	130	392	830	1186	1892	1657	782
5															
6															
7															
8															

Irrigation S1 | Irrigation S2 | Pu, t (S1) | Pu, t (S2) | **ETRM** | K1 | Kp | Af | Soil | S1 vs S2

Figure 6. The "ETRM" worksheet.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1																	
2																	
3	K1-Code	Latitude	Month	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX		
4	11	0	K1	1.04	1.01	1.04	1.04	0.94	1.04	1.01	1.04	1.01	1.04	1.04	1.01		
5	12	10	K1	1.02	0.98	0.99	1	0.91	1.03	1.03	1.08	1.06	1.08	1.07	1.02		
6	13	20	K1	1	0.93	0.94	0.95	0.9	1.03	1.05	1.13	1.11	1.14	1.11	1.02		
7	14	30	K1	0.98	0.89	0.88	0.9	0.87	1.03	1.08	1.18	1.17	1.2	1.14	1.03		
8	15	35	K1	0.97	0.86	0.85	0.87	0.85	1.03	1.09	1.21	1.21	1.23	1.16	1.03		
9	16	40	K1	0.97	0.86	0.81	0.84	0.83	1.03	1.11	1.24	1.25	1.27	1.18	1.04		
10	17	45	K1	0.94	0.79	0.75	0.8	0.81	1.02	1.13	1.28	1.29	1.31	1.21	1.04		*used in the example
11	18	46	K1	0.94	0.79	0.74	0.79	0.81	1.02	1.13	1.29	1.31	1.32	1.22	1.04		
12	19	47	K1	0.94	0.78	0.73	0.77	0.8	1.02	1.13	1.3	1.32	1.33	1.22	1.04		
13	20	48	K1	0.93	0.77	0.72	0.76	0.8	1.02	1.14	1.31	1.33	1.34	1.23	1.05		
14	21	49	K1	0.93	0.76	0.71	0.75	0.79	1.02	1.14	1.32	1.34	1.35	1.24	1.05		
15	22	50	K1	0.92	0.76	0.7	0.74	0.78	1.02	1.15	1.33	1.36	1.37	1.25	1.06		
16																	
17																	

Irrigation S1 | Irrigation S2 | Pu, t (S1) | Pu, t (S2) | ETRM | **K1** | Kp | Af | Soil | S1 vs S2

Figure 7. The "K1" worksheet. Data are taken from [34,47].

Initially, the cells from the rectangle C4–N4–N12–C12 in the "Irrigation S1" and "Irrigation S2" are empty. They are automatically filled in, concomitantly with the charts "WATER BALANCE" and "WATER RESERVE", after running the code.

The monthly precipitation and temperature series are introduced in the worksheets "Pu, t (S1)" and "Pu, t (S2)" (Figure 5). The data are entered consecutively for an unlimited

number of years for precipitation—in column C—and temperature—in D column D—separately. The worksheets (Figure 5) implement a 1–12 monthly average calculation module for both precipitation and temperature series. For performing the computation, the user can select all the years entered or a specific interval (for example, from year 5 to year 10) and press the button "Find Averages".

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1															
2															
3	Kp-Code	Description	Month	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX
4	11	corn (Constanta)	Kp	0.7	0.85	0.9	0.9	0.85	0.6	0.81	0.75	0.85	1.33	1.26	0.77
5	12	alphaalpha (Constanta)	Kp	1	1	1	1	1	1	1.6	1.11	1.01	1.07	1.15	0.97
6	13	corn (Tulcea)	Kp	0.7	0.85	0.9	0.9	0.85	0.6	0.94	0.61	0.98	1.29	1.28	0.81
7	14	alphaalpha (Tulcea)	Kp	1	1	1	1	1	1	1.53	1.32	1.33	1.27	1.3	1.19
8															
9															

Irrigation S1 / Irrigation S2 / Pu, t (S1) / Pu, t (S2) / ETRM / K1 / **Kp** / Af / Soil / S1 vs S2

Figure 8. The "Kp" worksheet. Data are reproduced from [35], p. 41.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1															
2															
3	Af-Code	Description	Month	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX
4	11	pesimistic	Af (m³/ha)	0	0	0	0	0	0	0	0	0	0	0	0
5															
6															
7															
8															

Irrigation S1 / Irrigation S2 / Pu, t (S1) / Pu, t (S2) / ETRM / K1 / Kp / **Af** / Soil / S1 vs S2

Figure 9. The "Af" worksheet.

	A	B	C	D	E	F	G	H	I
1									
2									
3	Soil-code	Location (zone)	Season	Culture (crop)	Soil texture data	Soil characteristics			
4						H or h (m)	DA(t/m3)	C0(%)	Cc(%)
5	11	Dobrogea	Winter	Corn	medium	1.5	1.29	6.9	23.2
6	12	Dobrogea	Summer	Corn	medium	0.75	1.3	7.5	24.15
7	13	Dobrogea	Winter	Sunflower	medium	1.5	1.29	6.9	23.2
8	14	Dobrogea	Summer	Sunflower	medium	1	1.28	7.4	23.9
9									
10									
11									

Irrigation S1 / Irrigation S2 / Pu, t (S1) / Pu, t (S2) / ETRM / K1 / Kp / Af / **Soil** / S1 vs S2

Figure 10. The "Soil" worksheet.

The average values obtained are automatically displayed in the table next to the series: the cells I3–T3 for the average monthly precipitation and I4–T4 for the average monthly temperature. Cells are also automatically filled in the table from the main worksheets—"Irrigation S1" (for the series introduced in "Pu, t (S1)") and "Irrigation S2" (for the series introduced in "Pu, t (S2)")—namely the cells C4–N4 (for the average monthly precipitations) and C5–N5 (for the average monthly temperatures). These values are then employed to calculate the irrigation rates.

When running the program, the user may introduce the corresponding code (11 in the cell Q6 in the worksheets "Irrigation S1" and "Irrigation S2" from Figure 6) for ETRM. If the evapotranspiration is known (such as in Figure 6), and data were previously filled in the worksheet "ETRM", the balance Equation (11) is computed using these values. If ETRM is unknown, the user must introduce the code "auto" in the cell Q6 in the worksheets "Irrigation S1" and "Irrigation S2", and the ETRM is estimated using Equation (3).

To not restrict the use of the tool for some specific soil types, the series of coefficients K_1, K_p, and A_f are entered by the user in separate worksheets with the same names.

The "K1" worksheet (Figure 7) already contains some K_1 values corresponding to different northern latitudes, among which is the 45° north latitude utilized in the exemplification. The table can be filled with values for other latitudes and the corresponding K1 code (assigned by the user). Two different latitudes must have different K1 codes.

The "Kp" worksheet (Figure 8) contains some examples of K_p values but can be filled with other values according to the crop and the region where it is cultivated. The user can assign the Kp code in column A and introduce any necessary description in column B.

In Figure 8 there are two types of crops—corn and alfalfa—and the corresponding coefficients for each location—Constanța and Tulcea. The values are filled in according to [35] for the two locations used for exemplification. For other locations and other crops, some values are provided in [33].

The K1 code and Kp code must be filled in the cells Q4 and Q5, respectively, from the main worksheets. When pressing the button "RUN Irrigation" from these worksheets, the corresponding K_1 and K_p values are filled in automatically in the cells C6–N6 and C7–N7, respectively, in the main worksheets.

The "Af" worksheet (Figure 9) contains the groundwater's supply values. The user can introduce them, and the code is filled in the cell Q6 from the main worksheets. When running the code, the values are automatically filled in the table from the "Irrigation S1" and "Irrigation S2" worksheets (the cells C8–Q8).

Figure 9 refers to the case when there is no water supply from the groundwater.

The "Soil" worksheet (Figure 10) contains the values of $H, h, DA_H, DA_h, C_{0,H}$, and $C_{0,h}$. It must be filled with the corresponding values for each soil type and each season. Since the soil characteristics are specific to the season, crop, and soil type, the user should specify (in column B) the location, the crop (column D), and season (column E).

The irrigation rate and watering numbers (abbreviated by "Water no." in the charts) are computed by pressing the command button in the "Irrigation S1" and "Irrigation S2" worksheets using Equations (1) and (2). The results and graphs are updated (the previous results are overwritten) both in the two main worksheets and in the comparison one ("S1 vs. S2") (Figure 11).
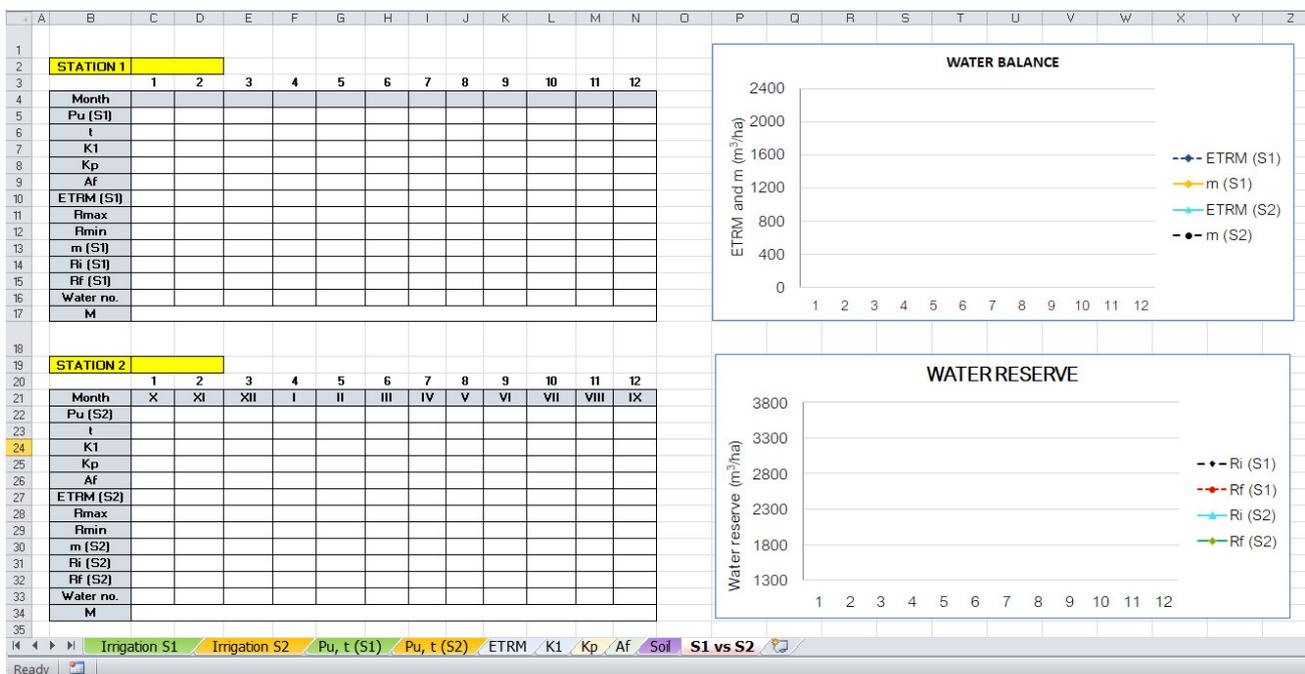

Figure 11. The "S1 vs. S2" worksheet.

5. Results

In the following, we exemplify how IrrigTool works, giving as input the monthly temperature and precipitation at Constanța and Tulcea (Romania) for 22 agricultural years (1998–2019). Given that the agricultural year starts in October (1 or month X in all the charts), the data series are introduced in the "Pu, t (S1)" and "Pu, t (S2)" worksheets. The chosen crop was corn.

Considering the geographical position of Romania, the K1 code represents the values of K1 corresponding to 45° northern latitude (Figure 7—C10).

The Kp code was chosen as 11 and 13 for CT and TL, respectively (Figure 8).

The water supply from groundwater was $A_f = 0$ because the region is arid, so the Af code was set to 11 (Figure 9).

The Soil code (Figure 10) for winter (summer) was the same, 11 (12), given the same soil characteristics. The ETRM code was set to "auto", so the ETRM was computed using Equation (3).

The initial water reserve in soil for October (Ri for month X) must be provided to start the computation. The user may introduce the value in the cell corresponding to "Ri for month X" from "Irrigation S1" and "Irrigation S2" or allow the software to compute it based on the formula (6) if "0" is inserted in that cell. The results obtained when the Ri for October is computed according to the methodology presented above are shown in Figure 12 (for CT) and Figure 13 (for TL), whereas their comparison is provided in Figure 14.

Row 15 in Figures 12 and 13 contains the watering numbers. One watering must be applied in June, August, and September and two in July for both locations. The water application rate is m = 812 m^3/ha (cells K12, M12, and N12, in Figures 12 and 13). The value 1623 from cell L12 in Figures 12 and 13 is equal to $2m$. The irrigation rate is 4058 in both cases (row 16 in the left-hand side table in Figures 12 and 13).

The "Water balance" charts (Figures 12 and 13) illustrate the mean monthly precipitation, ETRM, A_f, and m, whereas the second ones contain the water reserve (initial and final, maximum and minimum). The charts from Figure 14 summarize the findings for both locations.

The ETRMs are comparable at CT and TL. The initial and final water reserve is slightly higher at TL. The irrigation rate is the same at TL and CT. The watering should be applied the same month and in the same amount.

From Figures 12–14, row 30, it results that during the first eight months of the agricultural year (October–May), it is not necessary to apply irrigation. In June, August, and September, one watering should be applied (812 m^3/ha). In July, watering should be applied twice (a total of 1624 m^3/ha).

This aspect is emphasized in Figures 12 and 13, the bottom left chart, by the black dotted curves and in Figure 14, the top chart, by the yellow continuous curve (for CT) and the black dotted curve (for TL).

Given that the watering distribution depends on the initial soil reserve in October, the user may run the algorithm many times, at each run considering the initial water reserve in soil in October to be equal to the final water reserve in September in the previous run (and introducing manually this value in the cell "Ri for month X").
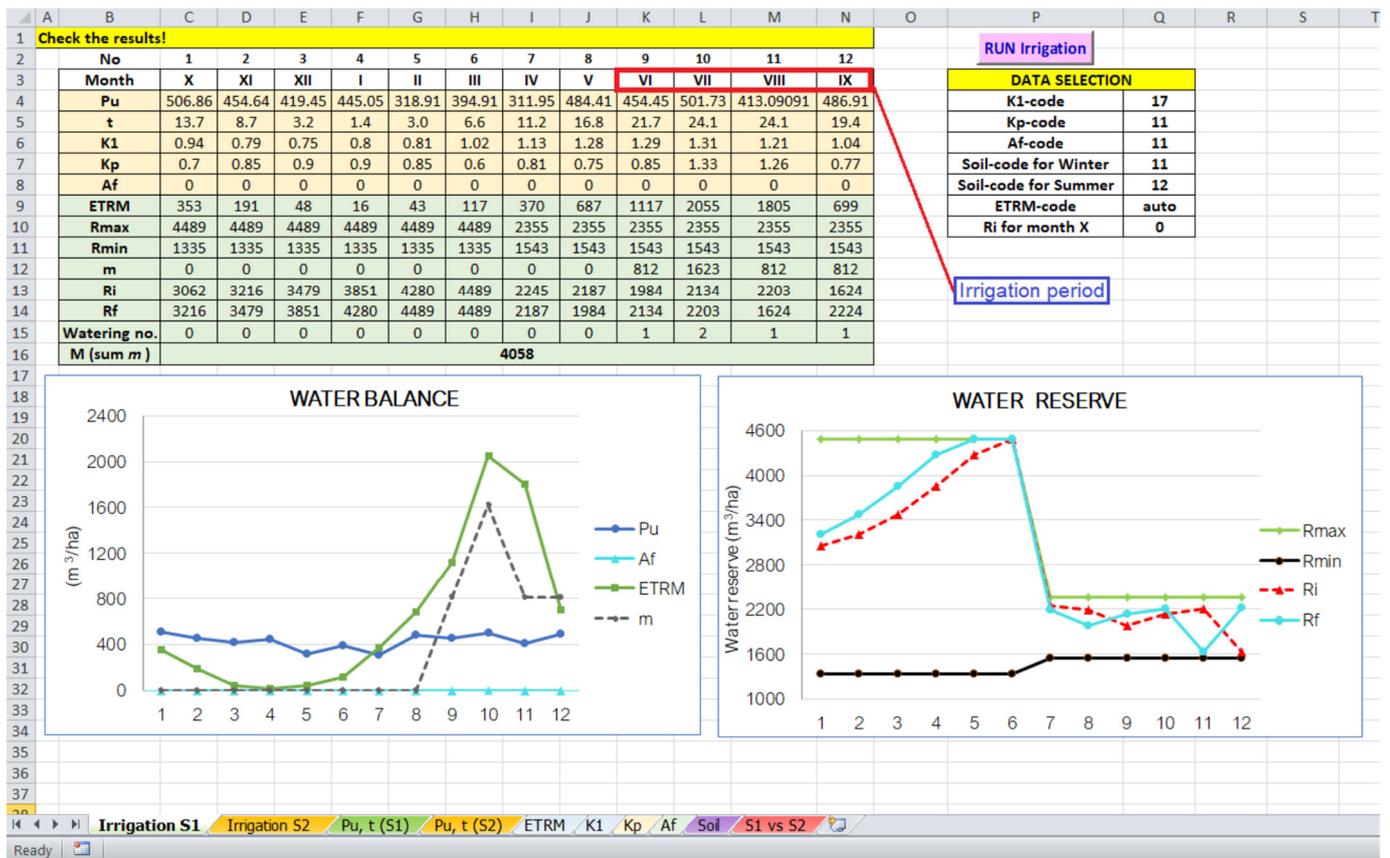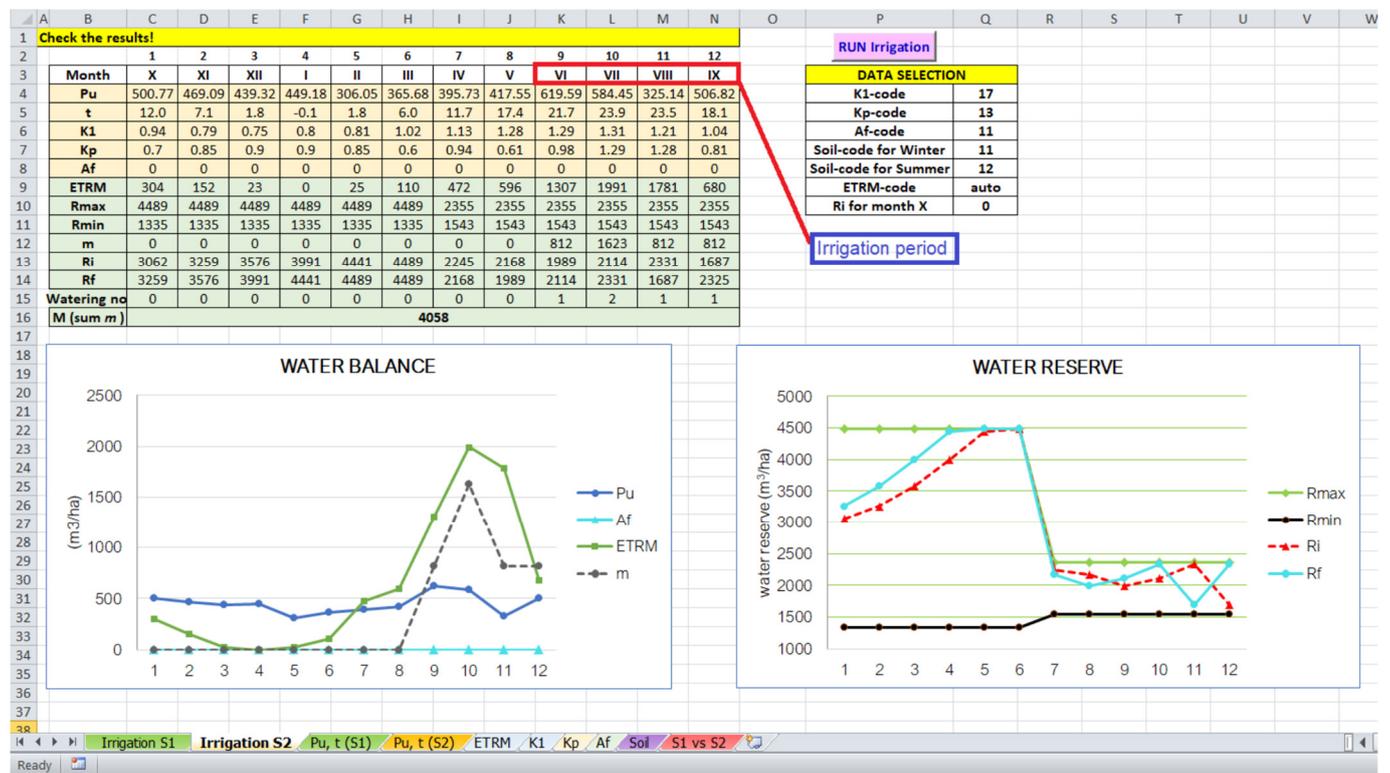
Figure 12. Computation results for CT.

Figure 13. Computation results for TL.

STATION 1	CONSTANTA	1	2	3	4	5	6	7	8	9	10	11	12
Month													
Pu (S1)		506.86	454.636	419.455	445.05	318.909	394.91	312	484.4	454.45	501.727	413.1	486.91
t		13.7	8.7	3.2	1.4	3.0	6.6	11.2	16.8	21.7	24.1	24.1	19.4
K1		0.94	0.79	0.75	0.8	0.81	1.02	1.13	1.28	1.29	1.31	1.21	1.04
Kp		0.7	0.85	0.9	0.9	0.85	0.6	0.81	0.75	0.85	1.33	1.26	0.77
Af		0	0	0	0	0	0	0	0	0	0	0	0
ETRM (S1)		353	191	48	16	43	117	370	687	1117	2055	1805	699
Rmax		4489	4489	4489	4489	4489	4489	2355	2355	2355	2355	2355	2355
Rmin		1335	1335	1335	1335	1335	1335	1543	1543	1543	1543	1543	1543
m (S1)		0	0	0	0	0	0	0	0	812	1623	812	812
Ri (S1)		3062	3216	3479	3851	4280	4489	2245	2187	1984	2134	2203	1624
Rf (S1)		3216	3479	3851	4280	4489	4489	2187	1984	2134	2203	1624	2224
Water no.		0	0	0	0	0	0	0	0	1	2	1	1
M							4058						

STATION 2	TULCEA	1	2	3	4	5	6	7	8	9	10	11	12
Month		X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX
Pu (S2)		500.77	469.091	439.318	449.18	306.045	365.68	395.7	417.5	619.59	584.455	325.1	506.82
t		12.0	7.1	1.8	-0.1	1.8	6.0	11.7	17.4	21.7	23.9	23.5	18.1
K1		0.94	0.79	0.75	0.8	0.81	1.02	1.13	1.28	1.29	1.31	1.21	1.04
Kp		0.7	0.85	0.9	0.9	0.85	0.6	0.94	0.61	0.98	1.29	1.28	0.81
Af		0	0	0	0	0	0	0	0	0	0	0	0
ETRM (S2)		304	152	23	0	25	110	472	596	1307	1991	1781	680
Rmax		4489	4489	4489	4489	4489	4489	2355	2355	2355	2355	2355	2355
Rmin		1335	1335	1335	1335	1335	1335	1543	1543	1543	1543	1543	1543
m (S2)		0	0	0	0	0	0	0	0	812	1623	812	812
Ri (S2)		3062	3259	3576	3991	4441	4489	2245	2168	1989	2114	2331	1687
Rf (S2)		3259	3576	3991	4441	4489	4489	2168	1989	2114	2331	1687	2325
Water no.		0	0	0	0	0	0	0	0	1	2	1	1
M							4058						

Worksheet tabs: Irrigation S1 | Irrigation S2 | Pu, t (S1) | Pu, t (S2) | ETRM | K1 | Kp | Af | Soil | **S1 vs S2**
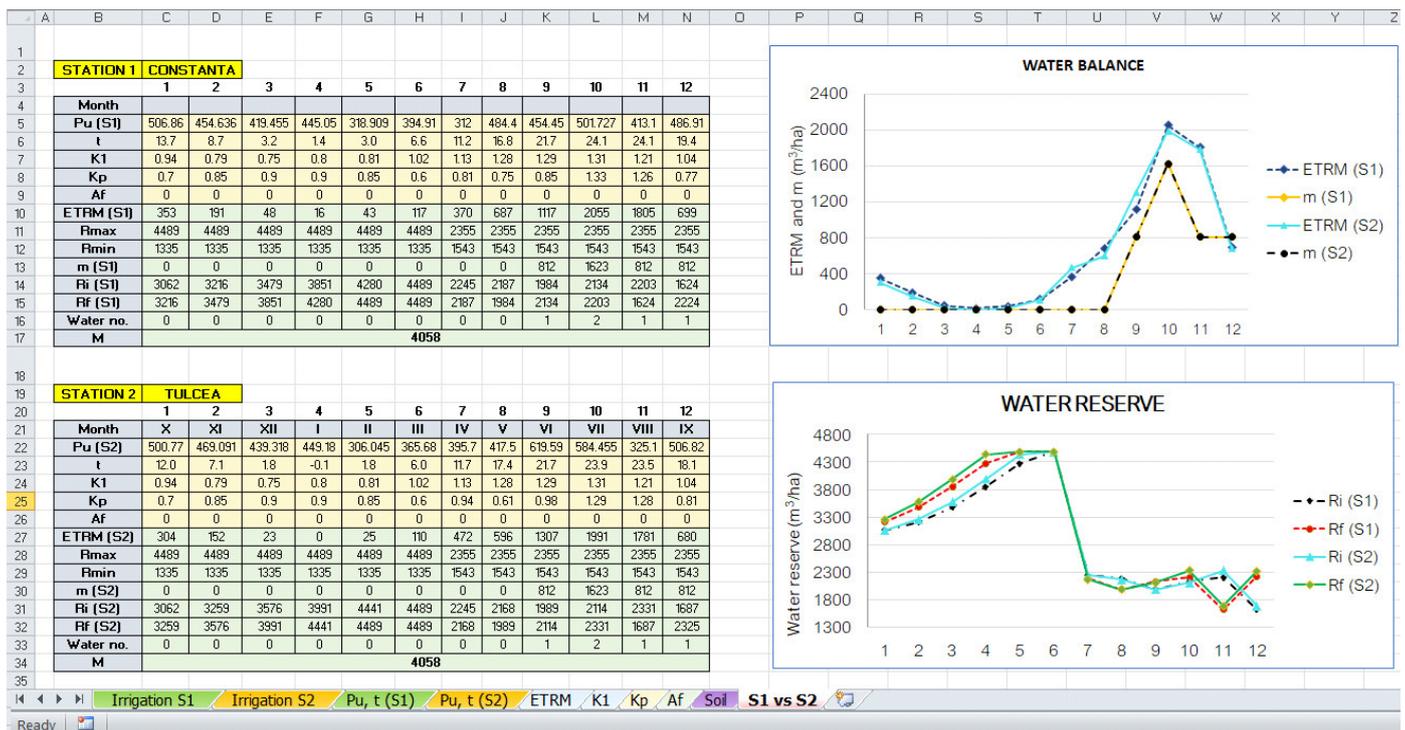
Figure 14. Comparison of the results for CT and TL (from the worksheet "S1 vs. S2").

6. Discussion

First, we compared the irrigation rate obtained using the Thornthwaite equation with the results obtained using the measured ETRM in the neighborhood of Constanța (at Mamaia). We mention that the procedure followed in Romania is that the ETRM is measured only for nine months, from March to November, so the rest of the values are considered to be zero. Therefore, IrrigTool was run with the ETRM code 12 in the worksheet "ETRM" (Figure 15). The output is shown in Figure 16.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
3	ETRM-Code	References	Month	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX
5	12	Mamaia	ETRM	325	204	0	0	0	104	322	692	1130	2055	1855	785

Worksheet tabs: Irrigation S1 | Irrigation S2 | Pu, t (S1) | Pu, t (S2) | ETRM | K1 | Kp | Af | Soil | S1 vs S2

Figure 15. Average ETRM values in the neighborhood of CT, at Mamaia (5 km from CT).

There are no significant differences between the computed and measured ETRM values—cells C9–E9 in Figures 12 and 16 and the watering numbers are the same (one in June, August, and September and two in July).

In the previous section, we indicated that the irrigation rate depends on the crop. To illustrate this assertion, we considered the crop alfalfa with the Kp code 12 (alfalfa). In this case, the soil code must be modified as well. In this case, it will be 15 for summer and 16 for summer (Figure 17).

The watering number has a different distribution: one in June and July and two in August. The irrigation rate is 4224 m^3/ha because, in this case, m = 1056 m^3/ha.

It was also mentioned that the irrigation rate depends on the initial water reserve in the soil. To exemplify, let us consider the same settings as in Figure 17, with Ri in the month 1 = Rmin in the month IX (2614 m^3/ha), and run the algorithm. In this case, one watering should be applied in from May to July. The irrigation rate will remain the same: 4224 m^3/ha (Figure 18).
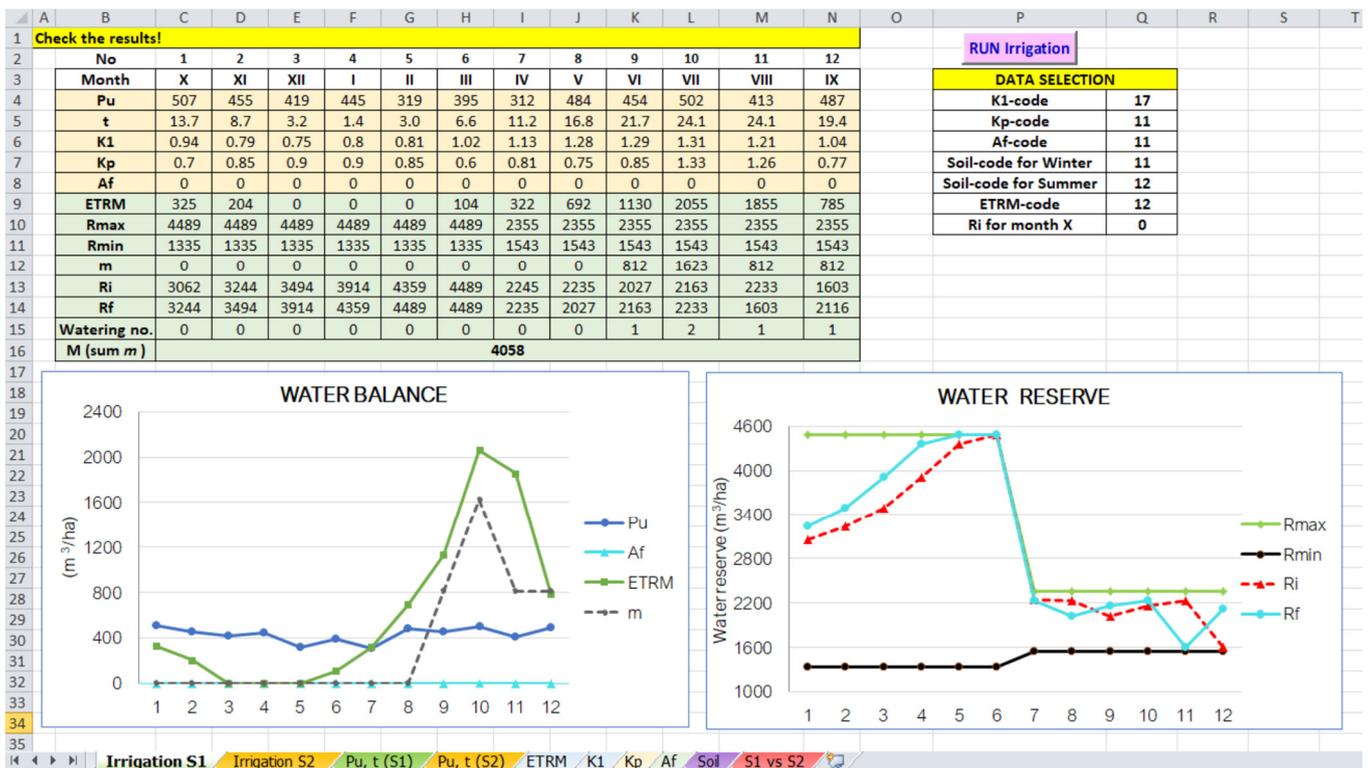
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1		Check the results!																		
2		No	1	2	3	4	5	6	7	8	9	10	11	12		RUN Irrigation				
3		Month	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX		DATA SELECTION				
4		Pu	507	455	419	445	319	395	312	484	454	502	413	487		K1-code	17			
5		t	13.7	8.7	3.2	1.4	3.0	6.6	11.2	16.8	21.7	24.1	24.1	19.4		Kp-code	11			
6		K1	0.94	0.79	0.75	0.8	0.81	1.02	1.13	1.28	1.29	1.31	1.21	1.04		Af-code	11			
7		Kp	0.7	0.85	0.9	0.9	0.85	0.6	0.81	0.75	0.85	1.33	1.26	0.77		Soil-code for Winter	11			
8		Af	0	0	0	0	0	0	0	0	0	0	0	0		Soil-code for Summer	12			
9		ETRM	325	204	0	0	0	104	322	692	1130	2055	1855	785		ETRM-code	12			
10		Rmax	4489	4489	4489	4489	4489	4489	2355	2355	2355	2355	2355	2355		Ri for month X	0			
11		Rmin	1335	1335	1335	1335	1335	1335	1543	1543	1543	1543	1543	1543						
12		m	0	0	0	0	0	0	0	0	812	1623	812	812						
13		Ri	3062	3244	3494	3914	4359	4489	2245	2235	2027	2163	2233	1603						
14		Rf	3244	3494	3914	4359	4489	4489	2235	2027	2163	2233	1603	2116						
15		Watering no.	0	0	0	0	0	0	0	0	1	2	1	1						
16		M (sum m)						4058												

Figure 16. Output of running the algorithm using ETRM recorded at Mamaia (5 km from CT).

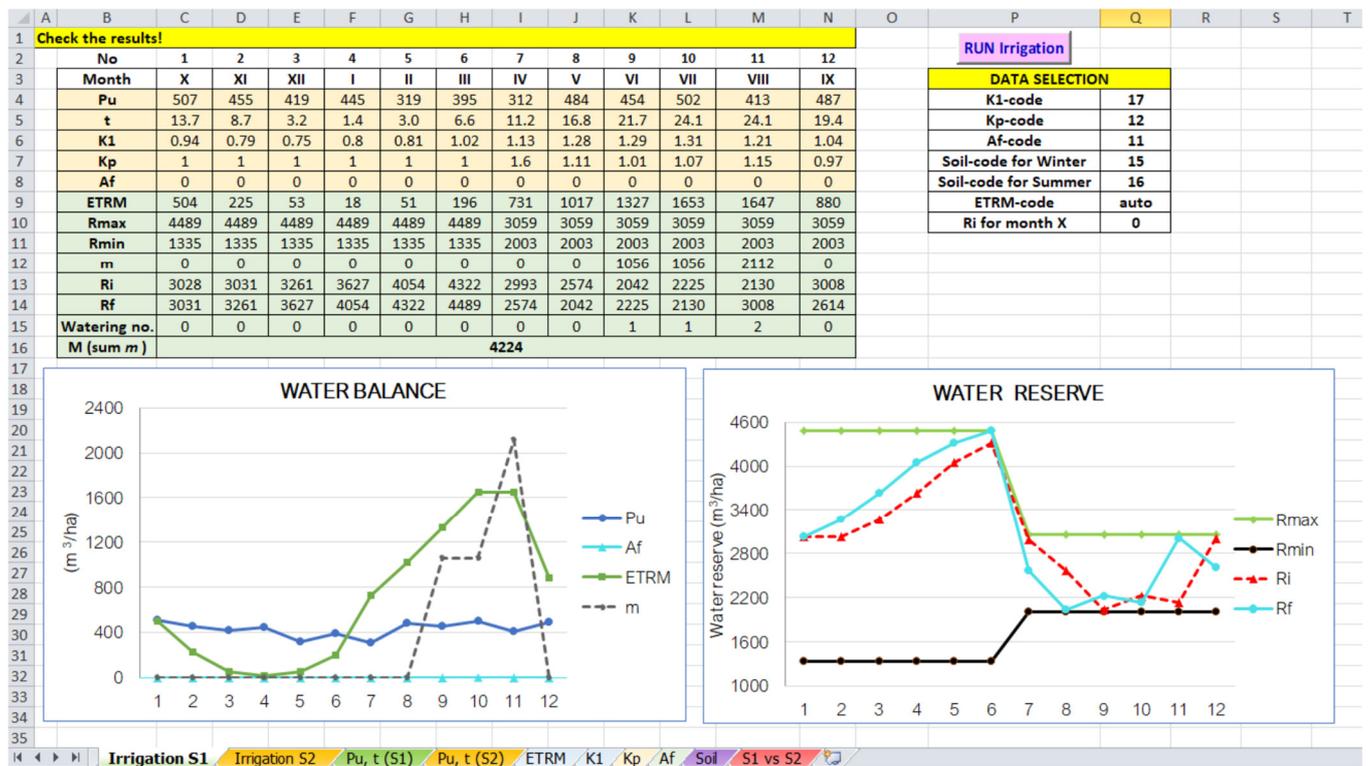|	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1		Check the results!																		
2		No	1	2	3	4	5	6	7	8	9	10	11	12		RUN Irrigation				
3		Month	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX		DATA SELECTION				
4		Pu	507	455	419	445	319	395	312	484	454	502	413	487		K1-code	17			
5		t	13.7	8.7	3.2	1.4	3.0	6.6	11.2	16.8	21.7	24.1	24.1	19.4		Kp-code	12			
6		K1	0.94	0.79	0.75	0.8	0.81	1.02	1.13	1.28	1.29	1.31	1.21	1.04		Af-code	11			
7		Kp	1	1	1	1	1	1	1.6	1.11	1.01	1.07	1.15	0.97		Soil-code for Winter	15			
8		Af	0	0	0	0	0	0	0	0	0	0	0	0		Soil-code for Summer	16			
9		ETRM	504	225	53	18	51	196	731	1017	1327	1653	1647	880		ETRM-code	auto			
10		Rmax	4489	4489	4489	4489	4489	4489	3059	3059	3059	3059	3059	3059		Ri for month X	0			
11		Rmin	1335	1335	1335	1335	1335	1335	2003	2003	2003	2003	2003	2003						
12		m	0	0	0	0	0	0	0	0	1056	1056	2112	0						
13		Ri	3028	3031	3261	3627	4054	4322	2993	2574	2042	2225	2130	3008						
14		Rf	3031	3261	3627	4054	4322	4489	2574	2042	2225	2130	3008	2614						
15		Watering no.	0	0	0	0	0	0	0	0	1	1	2	0						
16		M (sum m)						4224												

Figure 17. Output for alfalfa at CT, computed using the Thornthwaite equation.

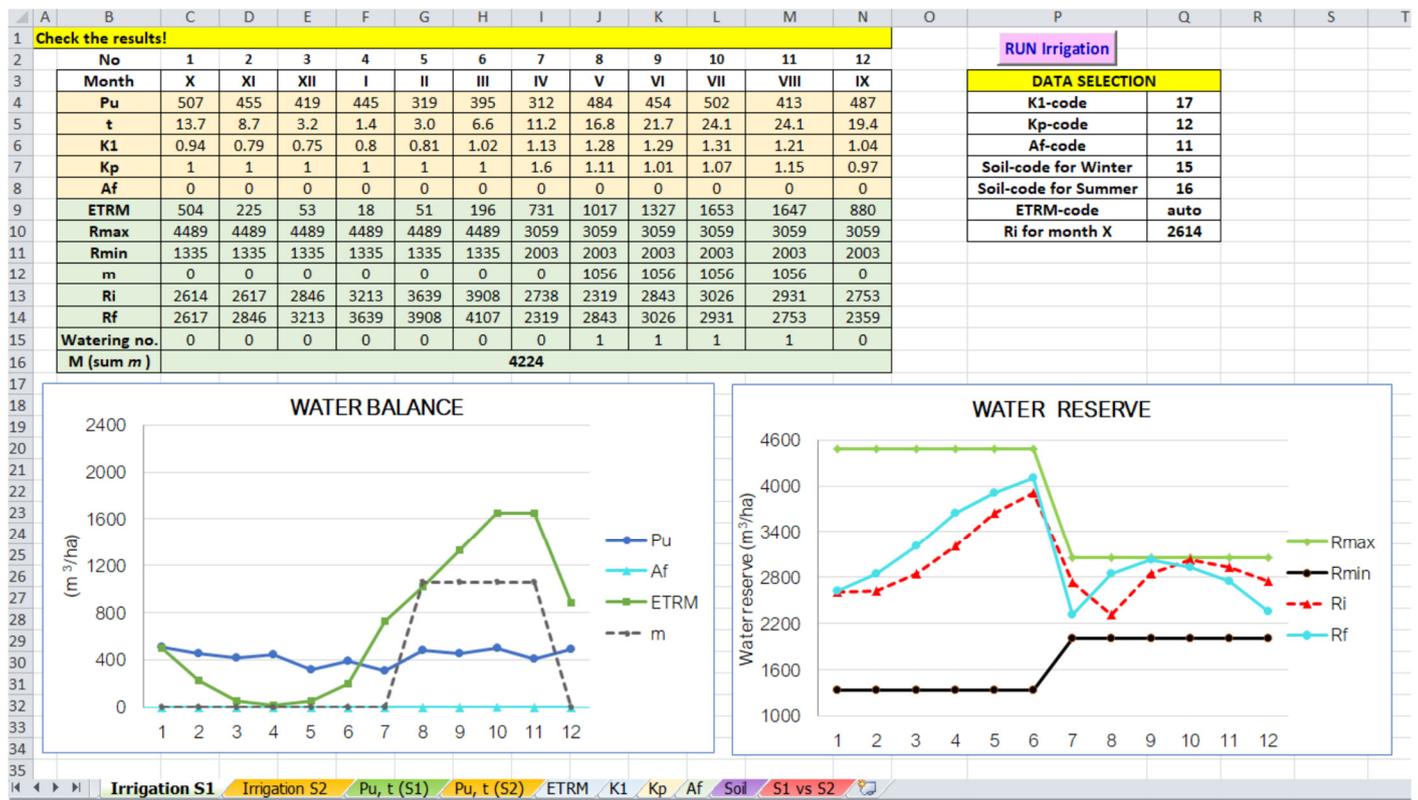**Figure 18.** Output for alfalfa at CT, computed by the Thornthwaite equation, with R_i = 2614 m^3/ha.

If the water reserve in the soil is known, it is indicated to use its value to better estimate the irrigation rate.

7. Conclusions

This article presented a new tool, IrrigTool, designed for computing the irrigation rate based on the Thornthwaite equation for ETRM. It is implemented in VBA and Excel and is easy to use without knowledge of the formula implementation. The user can introduce the data series in different worksheets whereby, during the computation, the programs import the data into the main worksheets. The output for two different data sets can be compared as series of numbers and graphically.

This tool's main advantage is that it permits the user to use either the Thornthwaite equation for ETRM computation or to manually fill in the recorded values of ETRM. Manually selecting or automatically computing the initial water reserve for the first month of the agricultural year is also permitted based on the available data. Moreover, there is no limitation related to the climatic conditions. The tool is user-friendly because it does not require programming skills but only basic knowledge of Excel.

A disadvantage of this tool is that the irrigation rate is computed only using the Thornthwaite equation (when ETRM is not known) and does not provide a comparison with another method. Therefore, in future work, we have the following goals: (a) to add a module that computes the ETRM by the Penman–Monteith equation and (b) to add a module to compare the irrigation rates computed based on the Thornthwaite and the Penman–Monteith equations.

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