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Justification of Plants Water Demand in Conditions of Drip Irrigation

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ABSTRACT

In the current work, a comprehensive methodology for the soil and climatic conditions of the Republic of Armenia has been developed to justify the water requirement/demand of plants in the case of drip irrigation. The proposed methodology enables to calculate the values of the individual components of the drip irrigation regime, and in practical terms, it was used to determine the water requirement of perennial plantations in the soil and climatic conditions of the Armavir and Kotayk marzes. Based on the obtained results, the crops drip irrigation norms/rates were mapped in the GIS environment. They can serve as a background for practical planning and justification of the drip irrigation water demand for various crops and contribute to the development of introduction rates of water-saving technologies in this field.

Introduction

The lack of a drip irrigation regime for crops in the Republic of Armenia and incomplete and unsystematized research on applied irrigation technologies cause serious obstacles to the upgrading and efficient management of irrigation networks. Currently, the drip irrigation systems introduced by various programs in different irrigation zones of the republic are designed and implemented in the absence of drip irrigation regimes for crops. Moreover, the irrigation regimes of agricultural crops developed in 2007 for the irrigated lands of the republic refer exclusively to surface irrigation. As a result, the farm households and water -supplying companies appear at a dead end when WUAs should make projections for water requirements and water distribution among diverse water users in the case of drip irrigation. Multiple studies have been conducted related to the individual components of drip irrigation. To thoroughly solve the problem, it is first necessary to investigate the dynamics of crop water demand under drip irrigation conditions depending on the biological characteristics of crops, their development stages, the depth of the root system spread, hydro-physical properties of the soil, and the complex influence of climatic and topographical conditions. The results of the conducted research will enable to evaluate the optimal water demand of crops, to develop drip irrigation regimes for crops distributed in different irrigation zones, to compare the indicators of drip irrigation with the surface irrigation regime, and to propose effective conditions for the design, construction, and operation of the drip irrigation system.

Materials and methods

One of the key issues in drip irrigation studies is the justification of crop water requirements depending on climate and soil conditions, crop type, agrotechnical, and irrigation techniques (Allen, et al., 2000; Yeghiazaryan and Miroyan, 2020).

Through the mathematical modeling of moisture movement in the unsaturated zone, the calculated formulae for the crops water demand determination depending on soil hydro-physical properties, root system depth, and planting patterns have been derived, the intensity of plants transpiration and the changing patterns of water amount in the leaves have been identified (Melikhova, 2015; Abakumova, 2006). Through the investigations, it was indicated that in conditions of drip irrigation the intensity of photosynthesis is higher than in the case of furrow irrigation. It has been found out that maximum yield can be ensured in conditions of 75…85 % field moisture capacity (Sheykin, 1980; Akopov, et al., 1985; Sahakyan, 2022). Despite the severe dry conditions in the case of drip irrigation, the plants demonstrate high resistance and even in case of 70 % of pre-watering soil moisture content they provide high yield capacity. The soil hydro-physical properties are less affected in conditions of drip irrigation in contrast to those of surface irrigation (Borodichev, et al., 2017; Davydenko, 2000; Gurenko, 2006). The constituent elements of the drip irrigation regime are the crops water consumption rate – ET_c, irrigation rate – M, watering rate – m, number – n and times – t of watering. The determination of water amount spent on the transpiration and physical evaporation in water consumption is related to certain difficulties and thus, it is very often determined as a single quantity. The total water consumption rate ET_c can be calculated through evapotranspiration ET_0. Anyhow, it is more relevant to determine the value of ET_0 with the FAO-56 method developed based on the Penman–Monteith equation, which is introduced through the following formula (Allen, 1996, Keller and Bliesner, 2000):

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{T+273} U_2\left(e_S - e_a\right)}{\Delta + \gamma\left(1 + 0.34U_2\right)}, \quad (1)$$

where ET_0 is the estimated evapotranspiration (mm/day), R_n is the radiation reached the crop surface (MJ/m^2.day), G is the radiation reflected from the soil surface (MJ/m^2.day), T is the air temperature at 2 m high above the soil surface – ^{0}C, U_2 is the wind speed at 2 m high (km/s), e_s is the pressure of saturated evaporations (kPa), e_a is the factual pressure of evaporations (kPa), Δ is the angular coefficient, Δ is the physical constant (kPa/ ^{0}C).

In the zones with unstable and somewhat dry moisture supply, under the drip irrigation conditions, it is relevant to determine the crops water demand for the years with 50, 75, and 95 % moisture supply. In the case of such an approach, in any year, it will be possible to provide the plants with such an amount of water, so as to get a high and sustainable yield. Considering the circumstance that the crops water demand is affected by multifactorial soil and climatic phenomena, it is expedient to evaluate the years with different moisture supply percentages per the deficit of evapotranspiration:

$$defET_0 = ET_0 - P. \quad (2)$$

The net rate of irrigation is determined by the following condition:

$$M_0 = \sum\nolimits_{i=1}^{n} M_{ni}, \quad M_{nj} = ET_{cj} - 10P_j\mu_j - \Delta W_j - K_j, \quad (3)$$

where M_{nj} is the net rate of irrigation at the i-th development stage of the crop, $10P_i\mu_i$ is the active reserve of atmospheric precipitations in the soil, ΔW_i is the active reserve of moisture in the soil at the given development phase – $\Delta W_i = W_{i=0} - W_{i=k}$. Depending on the soil and climatic conditions of the specific agricultural zone and the agro-biological peculiarities of the crops, the vegetation duration can undergo some changes T(day): If we assign the number of plants development stages as n and the duration of each development phase as t_j, then it can be stated that:

$$T = \sum\nolimits_{i=1}^{n} t_j . \quad (4)$$

According to the FAO-56 method, from the prospect of determining crops water demand it is reasonable to identify three development phases for the plants. The first phase is called initial – t_i, the second phase – the middle development phase t_{mid} and the third one – the final phase – t_{end}. Hence, it turns out that:

$$T = t_i + t_{mid} + t_{end}. \quad (5)$$

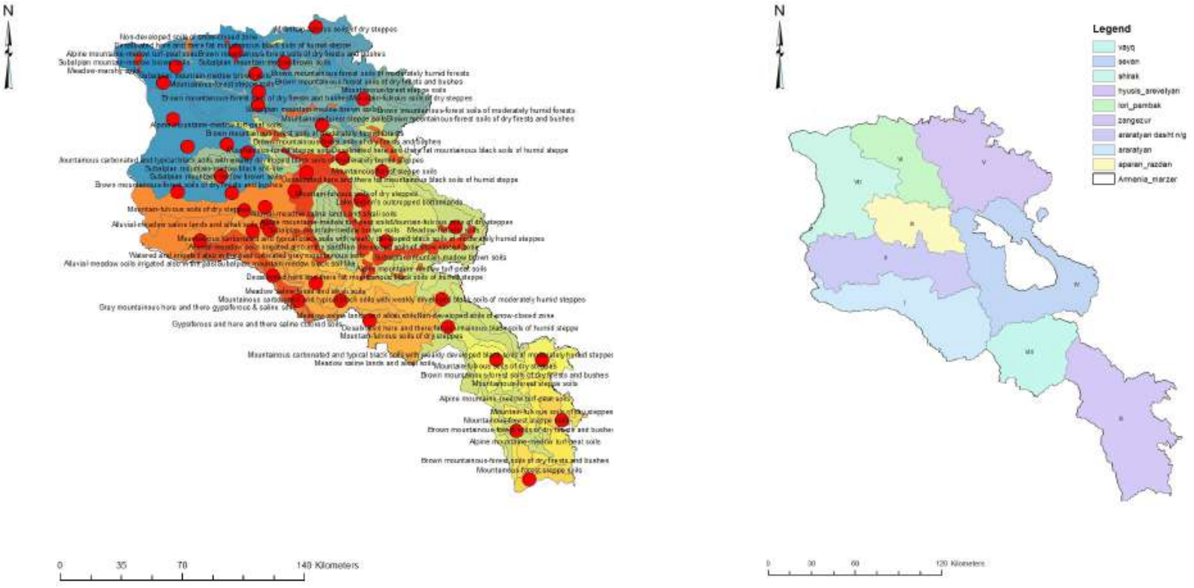

Figure 1. Digital maps of RA irrigation zones combined with the data of hydrometeorological stations and main soil types.

The value of transitional coefficient corresponding to the plant development stage is determined via the following relationship:

$$K_{cj}=\frac{ET_{cj}}{ET_{0j}}, \quad (6)$$

where ET_{cj} is the water amount consumed on the transpiration and evaporation from the soil surface per the plant development stage/phase under optimal agro-technical conditions, ET_{0j} is the evapotranspiration determined by climatic indexes. It is evident, that in certain conditions (climate, soil, crop variety, agro-technical conditions) the transitional coefficient, in its turn, is dependent on the following factors:

$$K_{cj}=K_{csoilj}*K_{cagritecj}*K_{ccropj}*K_{ctopogj}, \quad ET_c=\sum_{i=1}^{n} ET_{cj}. \quad (7)$$

The values of K_{csoilj}-coefficient are determined upon the following relationships:

$$K_{csoil}=\frac{1.5W_{wp}}{W_{FC}}. \quad (8)$$

Results and discussions

For the determination of evapotranspiration, the following parameters were obtained according to the data of meteorological stations retrieved for the period of 1992-2020: solar radiation, air temperature, relative air humidity, and wind speed. Evapotranspiration has been calculated with the support of the "CropWAT" application. Subjecting the obtained results to statistical processing, further calculations were conducted for the years with middle – 50 %, dry – 75 %, and extremely dry – 95 % moisture supply percentages. In the case of drip irrigation, it is recommended to identify the crops water demand per the irrigation zones, which correspondingly were classified according to their altitude above the sea level (Figure 1).

Table 1. K_{csoil} values depending on the soil mechanical composition, field moisture capacity (W_{FC}), permanent wilting point (W_{wp})*

Soil mechanical composition	W_{FC}	W_{wp}	K_{csoil}
Sand	12	4.5	0.56
Loamy sand	15	6.5	0.65
Sandy loam	23	11	0.72
Loam	25	12	0.72
Silt loam	29	15	0.78
Silt	32	17	0.80
Silt clay loam	33.5	20.5	0.92
Silt clay	36	23	0.96
Clay	36	25	1.04

*Composed by the authors.

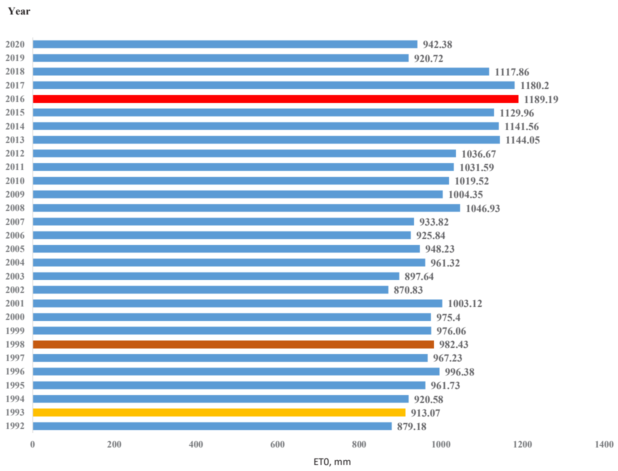

Figure 2. Dynamics of evapotranspiration during the vegetation period throughout 1992-2020 in conditions of Armavir region.

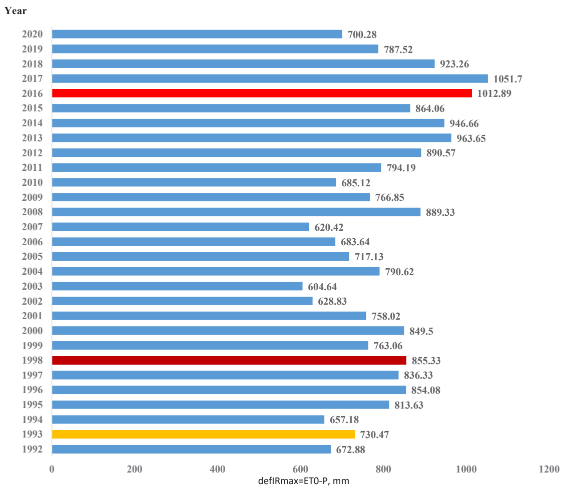

Figure 4. Dynamics of moisture deficit during the vegetation period throughout 1992-2020 in conditions of Armavir region.

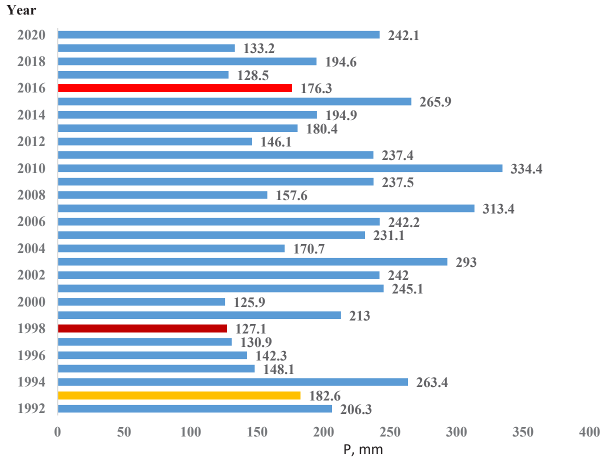

Figure 3. Dynamics of atmospheric precipitations during the vegetation period throughout 1992-2020 in conditions of Armavir region.

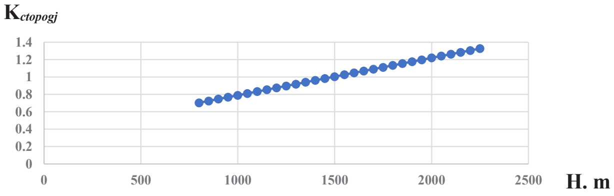

Figure 5. $K_{ctopogj}$ values per the altitudes above sea level (*composed by the authors*).

Table 2. Values of $K_{cagritecj}$ related to agro-technical conditions*

$K_{cagritecj}$ determined by agrotechnical conditions				
Grade	**Excellent**	**Good**	**Satisfactory**	**Unsatisfactory**
$K_{cagritecj}$	0.95	0.85	0.80	0.75

*Composed by the authors.

Depending on the soil mechanical composition, values have been calculated based on the quantities of Table 1.

The agrotechnical effect on the crops evapotranspiration is assessed through (Dual Crop) $K_{cagritecj} = K_{cb} + K_e$ value (Allen, 1996; Keller and Bliesner, 2000). The values of $K_{cagritecj}$ depending on agrotechnical conditions are presented in Table 2.

K_{ccropj} values are taken from Table 12 of Methodical Guideline “FAO Irrigation and Drainage Paper”. $K_{ctopogj}$ values describe the effect of absolute altitude on the total evapotranspiration. Taking into account the fact that the distribution of hydrometeorological stations according to irrigation zones in the territory of the republic is discrete and limited, it is recommended to use the dependence to switch from estimated evapotranspiration to total evaporation (Figure 5).

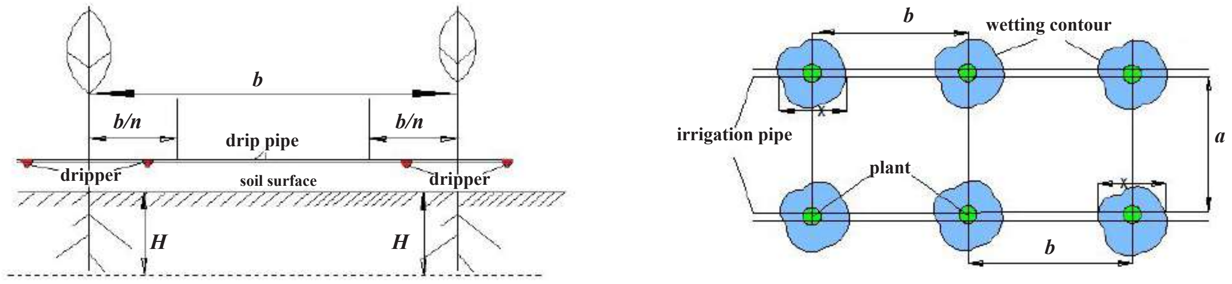

Figure 6. Linear technological diagram of drip irrigation (*composed by the authors*).

The following technological scheme is recommended to be taken as a background to identify the irrigation rate per the crops water demand (Figure 6).

The field study results of drip irrigation conducted by different authors indicate that the soil pre-watering moisture content fluctuates within 70…80 % (Akopov, et al., 1985; Davydenko, 2000; Sheynkin, 1980).

The amount of water that can evaporate from the root layer of the soil after fully moistening the soil is determined as follows:

$$TEW = 1000(W_{FC} - 0.5\,W_{WP})\,Z_e, \qquad (9)$$

where W_{FC} is the field moisture capacity, W_{WP} is the permanent wilting point, Z_e is the layer of soil surface that gets dry due to evaporation: 0.10…0.15 m. The maximum water quantity provided for a plant can be calculated through the following formula:

$$IR_{pp} = 0.01\pi R^2 H \alpha (W_{FC} - \beta W_{WP}). \qquad (10)$$

β values are determined:

$$\beta = \frac{\gamma W_{FC}}{W_{WP}}. \qquad (11)$$

The analysis of numerical values for different soil types of the republic shows that the values fluctuate related to the soil mechanical composition: thus, in the soils with heavy mechanical composition (silt, clay) its value ranges within 1.17-1.23, whereas in the soils with light mechanical composition (sand, silt clay loam, etc.) it is within 1.56-1.73. In the soils with middle mechanical composition the latter's value makes 1.41. After summing up the above stated numbers it becomes clear that a single amount of supplied water to one plant in the soils with heavy mechanical composition is reduced to the range of 6.6-8.8 %.

The data on water amount supplied to one plant in the case of drip irrigation with account for permanent wilting point (IR_1) and 75 % pre-watering moisture conditions (IR_2) is summed up in Table 3. The digital mapping results of irrigation water demand for perennial plantations in the soil and climatic conditions of the Armavir and Kotayk regions in the ArcGIS environment are presented in Figure 7.

Table 3. Water amount supplied for one plant in perennial plantations depending on soil conditions*

Soil mechanical composition	W_{FC}	W_{WP}	R	H	α	IR_1	IR_2
Sand	12	4.5	0.5	0.7	1.1	45.33375	34.45365
Loamy sand	15	6.5	0.5	0.7	1.1	51.37825	35.66255
Sandy loam	23	11	0.5	0.7	1.1	72.534	45.9382
Loam	25	12	0.5	0.7	1.1	78.5785	49.5649
Silt loam	29	15	0.5	0.7	1.1	84.623	48.356
Silt	32	17	0.5	0.7	1.1	90.6675	49.5649
Silt clay loam	33.5	20.5	0.5	0.7	1.1	78.5785	29.0136
Silt clay	36	23	0.5	0.7	1.1	78.5785	22.9691
Clay	36	22	0.5	0.7	1.1	84.623	31.4314

*Composed by the authors.

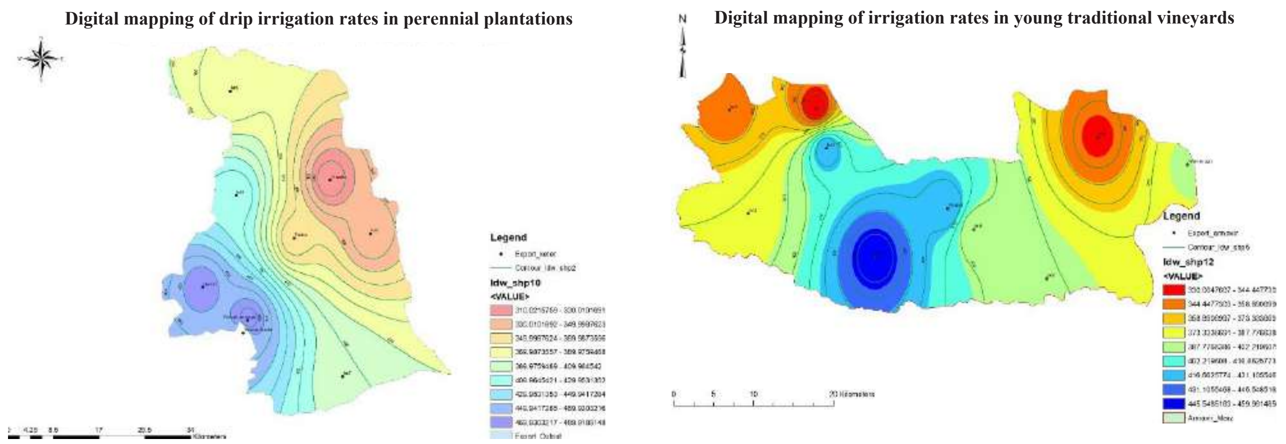

Figure 7. The digital mapping results of drip irrigation rates in conditions of Armavir and Kotayk regions.

Conclusion

An analytical model for determining the individual components of the drip irrigation regime has been developed, which takes into account soil, climatic conditions, and the phases of the biological development of the crop. The developed model has been applied in conditions of Ararat Valley and piedmont zones. Based on the obtained results the digital maps of crops water demand for vineyards and orchards in GIS medium have been compiled. The acquired results enable to plan and justify the crops water demand in case of drip irrigation in practice and to contribute to the development of introduction rates of water-saving technologies in this sector.

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