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CROPS WATER CONSUMPTION AND VERTICAL SOIL MOISTURE EXCHANGE

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ABSTRACT

A various number of factors, which, in turn, also vary greatly, determines the process of water consumption. These are meteorological indicators, yield, crop properties and soil conditions. The values of the water consumption of irrigated crops (in the operational regime of irrigation in the calculation of the water balance) are recommended to be determined counting on: the indicators of heat supply of the territories, that is, the radiation balance; air humidity deficit and bioclimatic factors of water consumption, taking into account the type and phase of plants development, the physical condition and the soil moistening. The empirical method for determining the vertical moisture exchange takes into account the biological characteristics of crops, the conditions for the heat and moisture availability of the calculation periods, the power and humidity of the soil layer under study, the water-physical properties of the ground, and the depth of the groundwater. It gives reliable results and can be used in calculations of the water regime in designing and exploitation of the reclamation systems. The groundwater affects the formation of the soil water regime in the aeration zone. At shallow occurrence, they increase the humidity in the root layer, which makes it possible to reduce the irrigation rates and the number of irrigation events. This article considers the problem of reducing errors and improving existing methods of calculating water consumption by crops and vertical soil moisture exchange. The methods of (Shebeko *et al*., 1980), Rogotskiy (1981) and Pylenok (1985) were taken as the basis of the research. According to them and empirical formulas developed by Mazaiski (2002), the calculations of vertical moisture exchange were made. The empirical method for determining the vertical moisture exchange takes into account the biological characteristics of crops, the conditions for the heat and moisture availability of the calculation periods, the power and humidity of the soil layer under study, the water-physical properties of the ground, and the depth of the groundwater. It gives reliable results and can be used in calculations of the water regime in designing and exploitation the reclamation systems.

Keywords: *soil moisture, water consumption, infiltration, radiation balance*.

INTRODUCTION

Soil moisture plays a crucial role in the hydrological cycle and climate system. The reliable estimation of soil moisture in space and time is important to monitor and even predict hydrological and meteorological disasters (Wang *et al*., 2018). Soil moisture dynamics have important impacts on theclimate–soil–vegetation system. A wide number of hy-drometeorological processes can be ascribed to water andenergy exchanges between soil and the near-surfaceatmosphere (Daly and Porporato, 2005). Soil moisture refers to the water present in the uppermost part of a field soil and is a state variable controlling a wide array of ecological, hydrological, geotechnical, and meteorological processes (Romano, 2014). The most agricultural climate change impact studies have focused on the impact on crop productivity (Mourice, 2017; Hatfield, 2011). However, changes in temperature, radiation and precipitation do not only affect productivity it also has an impact on plant water use. With agriculture being the number one water user across the globe changes in agricultural water use will have large impacts on water availability (Supit et al., 2010). Soil hydrological processes play an important role in land-atmosphere system. In most climate models, these processes are described by soil moisture variations in the first 2 m of soil resulting from precipitation, evaporation, and transpiration. Groundwater effects on soil moisture variations and surface evaporation are either neglected or not explicitly treated (Chen and Qi Hu, 2004). A huge number of factors, which, in turn, also vary greatly, determines the process of water consumption. These are meteorological indicators, yield, crop properties and soil conditions (Shebeko *et al.* 1980, Kapuściński, 2000). The close relationship of water consumption is noted with the radiation balance, and it has a close relationship with other meteorological factors (Bryś, 2013). The made experimental researches, statistical and correlation analyzes show that in the calculations of water consumption, the radiation balance or the deficit of air humidity can be used as meteorological factors (Bryś *et al*. 2018). The thermal energy presence for evaporation are indicators of moisture availability, have close relations with water consumption and heat costs for evaporation (Bac and Kuchar 2001).

MATERIAL AND METHODS

The study was conducted in the Ryazan district, Russia. According to natural data and the empirical formulas, the calculations of vertical moisture exchange were made. Object situated in Ryazan district, Russia, in Oka river basin; soil - sandy loam; surface slope 0,001-0,005; groundwater from 1-2 m to 8-10 m deep. Lysimeters were installed and groundwater levels were maintained at a depth of 0.7; 1.1; 1.5; 1.9 and more than 2.5 m with irrigation system help; drainage system 0.7-2.0 m depth. Biological properties of crops (lupine, potatoes and oats) were used: development phases; height; leaf surface area; biomass weight.

The soil moisture layer was taken differentiated according to the phases of crops development, taking into account an increase in the vegetation mass and 90% accumulation of the root system in it: 20-30 cm at the beginning and 30-50 cm at

the end of the growing season. Watering was carried out at a rate of 10-25 mm, increasing soil moisture to field capacity.
The study was carried on by using the daily average moisture deficit, average air temperature and daily precipitation, soil temperature, wind speed, radiation data of the Ryazan (Russia) meteorological station. According the empirical formulas, the calculations of vertical moisture exchange were made. The methodological basis of the work is the application of systematic and expert-analytical approaches to the organization of soil-ecological survey of the agrolandscape, with intensive anthropogenic impact, the development of ecologically safe two-way regulation of the water regime by irrigation and drainage, counting on vertical moisture exchange in the soil. The soil surveys, laboratory, field experiments, analytical researches and analyzes were carried out according to the methods of Shebeko (Shebeko *et al*., 1980), Rogotskiy (1981) and Pylenok (1985), as the basis of the crops water consumption calculation and vertical soil moisture exchange research:

$$V = 0{,}70\,B + 0{,}01 \qquad (1)$$

where V - heat loss by evaporation, mJ.

According the calculation method (1) Mazhayskiy (2002) derived the water consumption (E):

$$E = K_{sp}^{B} \cdot n \qquad (2)$$

$$E = K_{sp} \cdot d_{sr} \cdot n \qquad (3)$$

where B is the radiation balance, mJ/m^2;
d_{sr} - average saturation moisture deficit, hPa;
K_{sp}^{B} K_{sp} - bioclimatic coefficients of water consumption of agricultural crops;
n - duration of the calculation period, day.

The relation for the calculation of vertical moisture exchange (Mazhayskiy, 2002):

$$\pm M = a\Delta D^{v} K_w^{c} e^{dH} n \text{ , mm/day} \qquad (4)$$

where $\Delta D = (E\text{-}O\text{-}m)/n$ - water consumption deficit, mm/day;
$K_w = W_H/W_{HB}$ –relative soil moisture of the calculated soil layer,%;
H – depth of groundwater level from surface, m;
e – the base of the natural logarithm;
a, v, c, d - empirical coefficients;
O, m - precipitation and watering for the calculation period, mm;
W_H, W_{HB} - respectively, the actual soil moisture at the beginning of the period and at the level of the least water capacity,%.

The height of the capillary rise of moisture for sandy loam soils was taking into account, It was found that a noticeable recharge by groundwater of the root system of lupine is possible from a depth of 1.7 m, potatoes - 1.5 m, oats - 1.6 m. The vertical moisture exchange of the calculated soil layer with the underlying layers dependencies at ground water level depth 1.5–1.7 m (Mazhayskiy, 2002):

$$\pm M = a^1 \Delta D^{v1} K_w^{c1} e^{dH} n \,, \quad a^1 = ae^{dH} \,. \qquad (5)$$

According empirical formulas (4, 5) the calculations of vertical moisture exchange are made. The results were comparing with the actual data of lysimetric (variable and constant water level). Correlations between soil moisture in different depth were obtained.

RESULTS AND DISCUSSION

The water consumption were noted significant with total radiation, radiation balance and air humidity deficit (r = 0.85-0.64), significant with sunshine duration, temperature and humidity (r = 0.50-0.65), less stable - with wind speed, evaporation from the water surface, precipitation and soil temperature (r = 0.32-0.40) and are significant at a probability of 0.95-0.99. These values and characterizes the evaporation conditions per day more accurately in comparison with the average daily deficit. In turn, the radiation balance is significant correlated (r = 0.85-0.64) with the air humidity deficit, and then with the temperature and humidity of air. Thus, it is established that the fluctuation of water consumption of crops occurs synchronously throughout the day, and the maxima of these factors coincide with the true noon and occur at 2-3 pm in summer local time. Therefore, in the daily period, the relation between water consumption and radiation is linear in the phases of the crops development. The transition of the radiation balance from negative to positive values takes place an average of one hour after sunrise, and the reverse transition is observed in the evening, 1.5 hours before sunset. The water consumption coincides with the beginning and end of the sunshine. The duration of sunshine is largely a factor determining the radiation balance and the deficit of air humidity. The correlation coefficient is 0.99 between radiation balance and the heat costs was found. Uniform in biological development natural grass cover on the meteorological site with periodic underfeeding has a relatively constant water consumption. Therefore, the variability of the thermal factor- solar radiation has a significant effect on its dynamics, and the biological factor has a constant value. This increases the tightness of the connection and determines its linear nature. However, when analyzing the tightness of the connection between water consumption of potatoes and the radiation balance, a close relation can be traced only by periods of biological development. The features of intra-day dynamics of water consumption and meteorological factors and correlation analysis point to the existence of the water consumption connection both with the radiation balance and with a deficit of air humidity. Bioclimatic coefficients of water consumption of agricultural crops according (formula 2) and (formula 3) given in Table 1.

Table 1. Mean values of bioclimatic coefficients of the field crops water consumption

Culture	Indicators	Weeks from the time of field crops sowing (planting)							
		1	2	3	4	5	6	7	8
Lupine	K_{sp}^{B}	0.10	0.15	0.19	0.27	0.27	0.28	0.47	0.34
	K_{sp}	0.19	0.25	0.35	0.45	0.54	0.57	0.92	1.01
Potatoes	K_{sp}^{B}	0.10	0.10	0.15	0.23	0.25	0.30	0.32	0.35
	K_{sp}	0.15	0.17	0.27	0.31	0.53	0.53	0.68	1.42
Oats	K_{sp}^{B}	0.09	0.14	0.26	0.33	0.32	0.31	0.42	0.47
	K_{sp}	0.17	0.20	0.18	0.56	0.65	0.61	0.86	1.38
Culture	Indicators	Weeks from the time of field crops sowing (planting)							
		9	10	11	12	13	14	15	16
Lupine	K_{sp}^{B}	0.33	0.25	0.28	0.20	0.16	-	-	-
	K_{sp}	0.83	0.64	0.62	0.40	0.32	-	-	-
Potatoes	K_{sp}^{B}	0.27	0.31	0.35	0.30	0.26	0.22	0.28	0.11
	K_{sp}	0.86	0.70	0.73	0.62	0.62	0.42	0.45	0.19
Oats	K_{sp}^{B}	0.32	0.31	0.36	0.20	0.24	0.29	0.15	-
	K_{sp}	0.87	0.77	0.74	0.40	0.54	0.61	0.34	-

Note: K_{sp}^{B} K_{sp} - bioclimatic coefficients of water consumption of agricultural crops

The water regime of soil is largely formed under the influence of vertical moisture exchange in the aeration zone. The correlation ratio of the weekly values of the total moisture exchange in the aeration zone is: with the groundwater level - 0.44; moisture reserves at the beginning of the calculation period - 0.53; air temperature – 0.14; air humidity – 0.27; air humidity deficit – 0.33; water consumption – 0.38; the sum of precipitation and watering - 0.54; average daily water consumption for the calculation period - 0.60; the ratio of the average daily deficit of water consumption to relative moisture reserves in the calculated soil layer, expressed in fractions of least water capacity - 0.65 during the vegetative period of plants.

The relations between vertical moisture exchange, deficit of water consumption and soil moisture are curvilinear. Thus, during the periods of "flowering" and " tubers formation" of potato, the relations between vertical moisture exchange and water use deficit increases, the correlation ratio increases up to r = 0.86-0.92. The main determining factor for basin recharge is ground water level (r = 0.70-0.80), for infiltration - water consumption deficit (r = 0.60-0.90). An increase in basin recharge corresponds to an increase in the deficit of water consumption, a decrease in the moisture content of the root layer and the depth of groundwater. When irrigating these lands, vertical water exchange should be taken into account too, because on these conditions soil moisture exchange is different as the case of shallow depth of groundwater. The correlation between layers according formula (5) is 0.68-0.90 and the reliably at a probability of 0.95, 0.99. The obtained dependences can be used for water balance calculations of the water regime of meliorated lands with deep groundwater occurrence. They are applicable at relative humidity of soil (K_w) = 0,5-2,0. Empirical coefficients for vertical moisture exchange calculation according (formula 4) and (formula 5) given in Table 2.

Table 2. Empirical coefficients for vertical moisture exchange calculation

Culture	*ΔD*	Sandy loam soil						
		Drained H <1.5-1.7 m				$H \geq 1.5$-1.7 м		
		a	*v*	*c*	*d*	a^1	v^1	c^1
Lupin	>0	33.70	0.70	-1.95	-4.20	0.027	0.70	-1.95
	<0	0.32	0.34	1.92	0.10	0.379	0.34	1.92
Potatoes	>0	285.4	0.28	-3.92	-5.80	0.048	0.28	-3.92
	<0	0.32	0.34	1.92	0.10	0.372	0.34	1.92
Oates	>0	48.6	0.73	-2.79	-3.50	0.180	0.73	-2.79
	<0	0.32	0.34	1.92	0.10	0.376	0.34	1.92

Note: a, v, c, d - empirical coefficients

Taking into account the dependencies for determining water consumption and vertical moisture exchange for calculating the unsteady movement of groundwater according to the developed algorithm, water balance calculations were performed. It was found that on the drained sandy loam soil it is recommended to apply the formula (4) for vertical moisture exchange calculation, and at groundwater level H> 1.5 m for potatoes, H> 1,6-1,7 m for oats and lupines - formula (5). The vertical soil moisture exchange of the calculated soil layer should be taken equal to the deficit of water consumption with the opposite sign then H <0.5 m.

The biological features of the crops and the depth of the root system development significantly affect their values for sandy-loam soil. The regression coefficients for determining the negative component of vertical moisture exchange differ less significantly, as the moisture infiltration beyond the calculated layer of soil is a physical process. The groundwater levels in the calculations of the drained land according to the developed algorithm were dynamically (depending on the moisture content of the year) varied from 0.7 to 1.8 m. The oat uses the moisture of the underlying soil layers more fully. There is a significant moisture infiltration from the calculated soil layer into the underlying horizons on lands with a deep groundwater occurrence, so the total vertical moisture exchange is mostly negative. The values of vertical moisture exchange can be used in calculations of the soil water regime, in determining the value of irrigation norms and estimating the share of basin recharge in water consumption of plants. The results of the comparison show that the recommended method in this work gives the smaller errors in determining the vertical moisture exchange. The deviations of the calculated values from the actual ones vary from +5 to -12%.

CONCLUSIONS

Values of water consumption of agricultural crops and vertical moisture exchange in the soil in the regimes of water balance of agricultural reclaimed lands can be obtained only experimentally or as a result of calculations based on empirical relations. The values of the water consumption of irrigated crops (in the operational regime of irrigation in the calculation of the water balance) are recommended to be determined counting on: the indicators of heat supply of the territories, that is, the radiation balance; air humidity deficit and bioclimatic factors of water consumption, taking into account the type and phase of plants development, the physical condition and the soil moistening.

The empirical method for determining the vertical moisture exchange takes into account the biological characteristics of crops, the conditions for the heat and moisture availability of the calculation periods, the power and humidity of the soil layer under study, the water-physical properties of the ground, and the depth of the groundwater. It gives reliable results and can be used in calculations of the water regime in designing and exploitation the reclamation systems.

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