

APPLICATION DEPTH UNDER SPRINKLE IRRIGATION
AS AN ECOLOGIC AND ECONOMIC FACTOR

Nickolai S. Yorkhov*

ABSTRACT

For most natural conditions, the pre-runoff application depths (PRADs) under sprinkle irrigation are considerably less than the maximum application depths required to moisten active root zone from a critical soil water content to field capacity. Increasing the PRADs to some extent or up to the maximum application depth may prove to be an expensive activity. To justify such an activity, a thorough comparative economic analysis should be made involving various measures for increasing the PRADs and accordingly the actual application depths. Such an analysis becomes possible only if we know the influence of application depths on economically important parameters of a farm sprinkle irrigation system. Influence of application depths on the properly irrigated area, energy used for moving the sprinkle systems, and soil water evaporation is discussed in the paper.

Sustainable development of mankind is known to be an imperative of our time. Such a development envisages rational use of natural resources, to include mainly ecologic safety and economic optimum for any useful activity of man. That principle remains intact in relation to agriculture and to irrigated agriculture in particular.

The main ecologic problem of sprinkle irrigation is water erosion of the soil, that is irrigation erosion. It occurs when there is surface runoff of irrigation water during a watering process. Runoff results not only in soil erosion but in other detrimental ecologic and economic consequences as well.

To solve that problem many scientists recommend using criterion of allowable application rate. However that criterion proved to be inapplicable for solving the above mentioned ecologic problem. Based on the concept

*Assistant Professor, State University for Land Use Planning, Kasakov Street, 15, Moscow, Russia, 103064

of rational use of natural resources, the allowable application rate criterion does not allow a proper economic optimization of the erosion-safe sprinkle irrigation technology for a given setting of physical and economic conditions in which an irrigation system is to be constructed or reconstructed. The only proper criterion to be used for such a purpose is the pre-runoff application depth.

To ensure ecologic safety and economic efficiency of sprinkle irrigation, it is necessary that actual amounts of water applied per watering (per irrigation), actual application depths m , match the following conditions

$$\begin{aligned} m &\leq m_o \quad (\text{if } m_o \leq m_m), & (1) \\ m &\leq m_m \quad (\text{if } m_o > m_m), & (2) \end{aligned}$$

where m_o = pre-runoff application depth;
 m_m = maximum application depth.

Pre-runoff application depth is the maximum application depth which does not cause surface runoff and subsequently soil erosion during a watering process by a sprinkle system at a given field or plantation. Pre-runoff application depths change in the course of an irrigation season subject to seasonal changes in soil aggregate stability, plant cover of the soil, and other factors. Maximum application depth is a quantity of water required to moisten the active root zone, where most plant roots are available, from a critical water content to field capacity. Condition (1) ensures erosion safety of the sprinkle irrigation as well as prevents water loss through surface runoff whereas condition (2) extinguishes water loss through deep percolation. For most soils except those with very light sandy texture, the common case is the situation when the maximum application depths far exceed the pre-runoff ones,
 that is $m_o \ll m_{\max}$.

In many instances the pre-runoff application depths appear to be too small to meet some economic, operational and technical requirements. So a problem arises to increase the pre-runoff application depths. A great number of various measures suitable for increasing them have been proposed by many researchers. These measures include (a) choice of another sprinkle system with

lower application rate and/or smaller drops, or a lower height of their fall, (b) levelling the soil surface; (c) forming surface microbasins, pits, etc; (α) ripping the soil; (e) improving soil structure thus increasing its effective porosity and subsequently permeability, and many others. It is obvious that all these measures have their own costs. So in choosing the optimal option we should evaluate both costs and revenues resulting from increasing pre-runoff application depths. Thus the application depth becomes an ecologic and economic factor for optimizing the erosion-safe sprinkle irrigation technology.

The application depth influences the cost of irrigation in a different way for various types of sprinkle systems. For sprinkle systems which operate on a position (e.g. set-move sprinkle systems) smaller application depths lead to a lesser part of the working time being used productively for direct watering the soil while more time is spent to move the system to another position. As a result the seasonal irrigated area with an appropriate soil water content for a given sprinkle system is reduced for the year under consideration. With the reduced irrigation area specific annual irrigation costs (per unit of irrigation area) are consequently higher. Smaller application depths cause also higher operating costs, such as labour and energy costs through an increased number of waterings, as well as maintenance and repair costs.

For center-pivot sprinkle systems working on a single position we have another picture. In this case smaller application depths lead mainly to much higher energy costs, so far as these systems move continuously during a watering process filled with water while set-move sprinkle systems move to another position empty. But if center-pivots work on two or more positions their specific operating costs increase sharply. For all types of irrigation systems smaller application depths with shorter irrigation intervals lead to an increase in unproductive (or very low productive) water loss through soil water evaporation.

First let us examine influence of application depths on the irrigated area netto Ω^{nt} .

For a given sprinkle system with a discharge Q irrigated area

netto is calculated as follows

$$\Omega_i^{nt} = \frac{Q}{q_t}, \text{ ha}, \quad (3)$$

where Q = sprinkle system design capacity, l/s;
 q_t = specific irrigation technological discharge, that is discharge per unit area net, or irrigation hydromodule as we call it here in Russia, l/(s·ha).

$$q_t = q_c \cdot K_t, \text{ l/(s·ha)}, \quad (4)$$

where q_c = specific irrigation crop discharge, l/(s·ha);
 K_{nt} = natural and technological coefficient.

$$q_c = \frac{D_{\max}}{8.64}, \text{ l/(s·ha)}, \quad (5)$$

where D_{\max} = design daily irrigation requirement, mm/day.

It is worthwhile to note that the design daily irrigation requirement for a crop D_{\max} depends both on the climatic conditions of the site and the adopted sprinkle irrigation technology because the latter includes the pre-runoff application depths. Recommendations on the design daily irrigation requirements available here in Russia are usually based on field experimental data obtained with maximum application depths. So some kind of correction is needed in the course of iterative optimization process of the erosion-safe sprinkle irrigation technology.

The natural and technological coefficient K_{nt} is estimated as follows

$$K_{nt} = \frac{1}{\alpha\beta\gamma\delta\varepsilon} \quad (6)$$

where α = parameter showing what part of the day the sprinkle system is able to operate (during the peak water requirement period);

β = parameter reflecting technologic losses of the working time;

γ = parameter that takes into account possible loss of the working time for operational repairs of the sprinkle system;

δ = parameter revealing possible loss of the working time due to failure of the turnouts, pumps or conveyance system;

ϵ = parameter that allows for drop evaporation and drift loss;

ν = parameter showing what part of the peak water requirement period could be actually used for irrigation without strong or gusty wind.

For a given type of sprinkle system, influence of the application depth on the adequately irrigated area is expressed mainly through parameter β . It can be elaborated as follows

$$\beta = \frac{t_w}{t_w + t_i} \quad (7)$$

where t_w = duration of direct watering the soil for a technologic time;

t_i = total technologic interruption in direct watering the soil attributed to a technologic time.

$$t_i = t_{i1} + t_{i2} + t_{i3}, \quad (8)$$

where t_{i1} = duration of interruption in direct watering the soil for a technologic time;

t_{i2} = the same for a technologic cycle attributed to a technologic time;

t_{i3} = the same for a technologic period attributed to a technologic time.

Under a technologic time we understand the least common periodically repeated technologic process that is a part of a longer technologic cycle which in its turn is a part of the most prolonged technologic period.

Multiplying numerator and denominator of the proper fraction (7) by the average effective application rate we get

$$\beta = \frac{m}{m+m_i}, \quad (9)$$

where m = actual application depth;
 m_i = unrealized application depth that is the depth of water that could have been applied during total technologic interruption in direct watering the soil.

For example, if we compare two options of an identical side-roll set-move irrigation system working on the same field with $m_1 = 15$ mm and $m_2 = 60$ mm (pre-runoff application depth in the second option is higher thanks to special measures), $t_i = 60$ min, $\rho = 0.2$ mm/min (about 0.47 iph), then the area properly irrigated in the second option will be half as much again as in the first one. For another example, if we choose a type of an irrigation system with the same discharge from two options: side roll ($\rho = 0.2$ mm/min, $m = 30$ mm, $t_i = 60$ min) and center-pivot ($m = 30$ mm, $t_i = 0$), then we shall find that the pivot will irrigate an area that is 40% more than the side-roll.

In general for any sprinkle system its specific farm irrigation system costs (that is costs attributed to a unity of properly irrigated area) are directly proportional to

$$k = \left(1 + \frac{m_i}{m}\right) \quad (10)$$

Specific annual energy used for linearly moving laterals within an irrigated area can be expressed as follows

$$e = m_s g k_r \frac{2M}{m} \quad (11)$$

where e - specific annual energy, N;
 m_s - specific linear mass of a sprinkle lateral, kg/m (see Table 1);

$$m_s = \frac{M_s}{B_o}$$

where M_s - sprinkle lateral mass, kg;
 B_o - effective length of the sprinkle lateral
 (effective length of the rain zone), m;
 g - acceleration of gravity;
 k_r - resistance coefficient;
 M - seasonal irrigation requirement;
 m - average application depth.

Table 1. Specific linear mass of some sprinkle systems

Type of sprinkle system	Specific linear mass, kg/m	
	dry	with water
Side-roll wheel-move «Volgianka»	6.8...8.4	-
Wheel-mounted sprinkle laterals driven with electric motors «Dniepr»	30	-
Hand-move KI-50-1A (except pump)	2	-
Tow-move with boom sprinklers ShD-25-300A	6.25	-
Linear-move «Kuban»-L 200/800	52	83
Linear-move «Tavria» 200/800	52.5	84
Irrigation machine carrying sprinkle lines mounted on a tractor DDA-100MA	90	92
Center-pivot «Fregat» (hydraulically moved)	32	50...55
Center-pivot «Kuban»-LCI moved with electric motors	42...45	67...72

Similar formula like (11) can be used for center-pivots but without the coefficient 2. The factor of application depth is sure to play a more significant role in arid natural conditions and for more water-consuming crops.

We can see from the Table 1 that the specific linear dry mass for many set-move sprinkle system is several times less than that for continuous-move system. Thus the latter systems use much more energy for moving lat-

erals filled with water as compared with the set-move system.

An approximate evaluation of influence of application depths on unproductive loss of water through evaporation from the soil surface (or very low productive) can be made with the use of a procedure described by L.G. James (1988). According to the procedure the crop coefficient K_c for the first growth stage is estimated as follows

$$K_c = a (ET_0)^b, \quad (13)$$

where ET_0 = potential evapotranspiration or reference crop ET;

a = coefficient from Table 2;

b = exponent from Table 2.

Values of a and b were given by L.G. James as depending on average interval of irrigation or rainfall t_w (days), which can be determined as a function of the application depth m and average daily irrigation requirement D_t (mm/day) for the period of t_w :

$$t_w = \text{---} \cdot (t_w \geq 1) \frac{m}{D_t} \quad (14)$$

Calculations show through the coefficient K a steady increase in evapotranspiration with the decrease of irrigation intervals t_w as compared to the ET for an irrigation interval $t_w = 7$ days (Table 2).

Table 2. Increase in evapotranspiration for the first growth stage with decrease of irrigation intervals t_w (James, 1988)

t_w , days	7	6	5	4	3	2	1	0
a	0.742	0.790	0.844	0.904	0.976	1.049	1.134	1.250
b	-	-	-	-	-	-	-0.030	0.125
	0.319	0.288	0.254	0.216	0.175	0.119		
K	1	1.16	1.26	1.44	1.66	1.95	2.43	3.44

Average daily level of Et_0 during growth stage 1 is taken to be 5 mm/day.

Values of a and b for $t_w < 2$ days are graphically extrapolated, and for $t_w = 3, 5$ and 6 - interpolated.

Another approach was used by Jordanian scientists (Al-Qinna, Abu-Awwad, 1998), who fitted their field experimental data with the following formula

$$E_{ws} = K_w K_t, \quad (15)$$

where E_{ws} = average daily soil water evaporation under sprinkle irrigation, mm/day;

K_w - potential daily soil water evaporation during the day of irrigation in the experiment, mm/day;

K_t - coefficient reflecting a decline in daily soil water evaporation during days following irrigation.

$$K_t = 1 - \sqrt{t_w/t_d}, \quad (16)$$

where t_w - day number after irrigation (on the day of irrigation $t_w = 0$);

t_d - time period needed for the soil to become dry after irrigation (for the experiment $t_d = 5$ days).

According to a well-known model for soil water evaporation which can be found in any full enough textbook on soil physics, the time period t_d corresponds to transition of the soil water evaporation process into the third stage. In that stage soil water evaporation is very low and subsequently it can be neglected. Calculations using formula (16) also show a considerable increase in soil water evaporation under more frequent light irrigations as compared with more heavy and seldom ones (Table 3).

Table 3. Increase in soil water evaporation (K) with the decrease in irrigation intervals (t_w) according to formula (16)

t_w , days	5	4	3	2	1	0
K_t	0	0.106	0.225	0.368	0.553	1
K	1	1.20	1.43	1.71	2.07	2.67

As we can see from Tables 2 and 3, shorter irrigation intervals t_w (and smaller application depths m) may result in a considerable increase in water requirement for irrigation.

The material presented and discussed in the paper show strongly the necessity of taking into account the factor of application depths under sprinkle irrigation in any ecologic and economic optimization process for the construction and reconstruction of irrigation systems on the base of the concept of rational use of natural resources.

REFERENCES

1. M.G. Al-Qinna, A.M. Abu-Awward. 1998. Soil water storage and surface runoff as influenced by irrigation method in arid soils with surface crust // Agr. Water Manage. 37 (3): 189...203.
2. L. G. James. 1988. Principles of Farm Irrigation System Design.- John Wiley and Sons.- 543 p.