EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2025, 26(5), 229–236
https://doi.org/10.12912/27197050/203220
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Received: 2025.02.24
Accepted: 2025.03.25
Published: 2025.04.01

Substantiation of parameters of moisture retention in arable land using mining wastes

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ABSTRACT

The article is devoted to the substantiation of the parameters of the method of accumulation and retention of rain and irrigation water in agricultural fields, reducing its losses due to evaporation and convective removal. To preserve water in arable land, it is proposed to arrange parallel rows of grooves of a certain depth and width, which are filled with fine material, mainly mining waste – burnt-out waste heaps. The design of a device for implementing the method is proposed taking a seeder as a basis. The most probable parameters of the method, groove width and depth and the distance between the groove rows, are substantiated in practice. For the first time, the dependence of the water accumulated in arable land on the parameters of the proposed method was theoretically obtained in the form of a polynomial regression equation. Statistical analysis has confirmed the sufficient reliability and significance of the results. The obtained research results can be used to substantiate the rational parameters of the technology of water retention in agricultural fields.

Keywords: mining wastes, irrigation water, water retention in agricultural fields.

INTRODUCTION

Water is the main decisive resource of agricultural production. According to the Food and Agriculture Organisation of the United Nations, about 70% of the total freshwater intake on the planet is used in irrigation systems, which creates a significant burden on water demand in other sectors of the economy, especially in heavy industry (FAO, 2021). In developing countries, due to limited financial resources and imperfect irrigation systems, this figure can generally be as high as 95% (Mansingh et al., 2023).

Ukraine has a high potential for effective management and further development of agriculture, due to its fertile soils, favourable climatic conditions, and available labour resources (Vozniuk et al., 2023). A crucial factor limiting the productivity of Ukrainian arable land is the shortage of irrigation resources. This applies to both quantitative and qualitative characteristics of irrigation water. In terms of quantitative indicators, compared to

European countries, Ukraine has a smaller water resource per unit area, with the amount of water in the eastern and southern territories being three to five times less than the average for Ukraine (Stelmakh et al., 2023). Thus, in Donbas, the shortage of natural water resources is associated with the unique vaulted topography of the region, due to which all rivers flow into the Azov and Black Seas. At the same time, the main sources of water supply are precipitation, groundwater, and highly saline wastewater from communities and enterprises, including coal mines (Denisov et al., 2017; Kostenko et al., 2018; Gavrishin, 2018), which negatively affects the quality of irrigation resources (Kostenko et al., 2022a).

Changes in the thermal regime in Ukraine due to global warming have led to an increase in the temperature load on the arable land surface and a shift in the boundaries of agroclimatic zones. In summer, the daytime air temperature in Ukraine is in the range of 30–35 °C, determining intensive evaporation of moisture, while, according to studies (Yatsyuk et al., 2021; Christidis et al., 2021), the average air temperature is expected to increase by 2 to 4 °C in the coming years. The heating of the earth's surface exceeds this figure by tens of degrees, which provokes significant wind flows above the earth's surface and in the vertical direction. Wind is an essential component of the process of forced convection, which, along with natural convection, determines the intensive removal of moisture from the soil surface.

Over the past half century, precipitation patterns have changed somewhat in the south-eastern part of Ukraine. Their total volume in the warm season has remained almost unchanged, while the rain-free period and the intensity of single rainfall have increased significantly. Despite the over-drained arable land, usually the shock-load of rainwater does not have time to seep deep into the ground, and therefore a significant part of it is lost, flowing to rivers and the sea. In spring, there is significant precipitation, which often leads to flooding, and in summer there is almost no rain. Thus, in the Pokrovsk community of Donetsk region in 2021, there was no significant rainfall from May to the end of August. Drought causes significant losses in agricultural production, which is associated with rising food prices (Bohomaz et al., 2023).

The growing deficit of freshwater resources in agro-industrial countries requires a rational approach to its economical use. Therefore, farmers are increasingly abandoning traditional plant irrigation, which means irrigation of the soil surrounding the plant, in favour of modern irrigation technologies, such as drip irrigation systems, well systems or injection irrigation. Modern irrigation systems are mostly automated and aimed at minimising water loss and distributing it evenly over the irrigated area (Askaraliev et al., 2024; Ramachandran et al., 2022).

One example of a modern method of irrigation is injection irrigation, which means that irrigation water is supplied directly to the xylem of plants and therefore is only used for transpiration. The use of injection irrigation can reduce water losses by 80–86% compared to traditional irrigation, which is explained by the fact that in traditional irrigation, a significant part of irrigation water, in addition to transpiration, is spent on physical evaporation and infiltration (Zubairov et al., 2015). The use of injection irrigation is advisable on small agricultural plots, it does not require the construction of expensive elements of the irrigation system – pumping stations, canals, hydraulic structures, which can be considered as an advantage. The disadvantage is the complexity of mechanisation of the injection technology and the excessive cost of scaling up to large areas.

Drip irrigation has gained wide popularity, which has several options, depending on the method of water supply: submembrane, underground and aeration (Arshad, 2020; Moursy et al., 2023; Cui et al., 2020; Zang et al., 2020). The use of drip irrigation, unlike traditional methods, significantly reduces the wasteful use of water through evaporation and seepage (Flores et al., 2021; Fukai et al., 2022), reduces soil erosion and nutrient loss. Drip irrigation delivers water directly to the plant root in an organised manner, which reduces water consumption and improves soil quality by preventing crusting on its surface. It has been proven that drip irrigation significantly increases crop yields, namely by 28.92%, 14.55%, 8.03%, 2.32% and 5.17% compared to flood irrigation, border irrigation, furrow irrigation, sprinkling, and micro-sprinkling, respectively (Yang et al., 2023). Furthermore, the use of drip irrigation can reduce the cost of electricity and labour.

However, the use of drip irrigation technology requires an integrated approach, which consists in a thorough study of the physical and mechanical properties of the soil, which significantly affect the nature of water distribution. Specifically, on coarse textured soils, the wetting zone and seepage rate are lower than on loose soils, which leads to poor soil aeration and a decrease in crop quality and yield. In some cases, the water pressure in the area around the water sprayer can exceed atmospheric pressure, thus changing the direction of water flow towards the soil surface (Bajpai et al., 2020).

Moreover, drip irrigation is associated with the generation of copious amounts of plastic and rubber waste. This is due to the fact that the drip fuel system is made of thin rubber pipes that have a limited service life. The main problem of drip irrigation is clogging of the holes through which water enters the plants with various kinds of fine debris and the root system of plants, which determines the need for timely and regular maintenance and repair (Saxena, 2021; Jayant et al., 2022).

An analysis of modern irrigation technologies used in the agricultural sector has shown that they are mostly aimed at the rational use of water and its uniform distribution over the irrigated area and do not address the issue of water accumulation in arable land. Therefore, it is necessary to consider the possibility of artificially changing the filtering properties of the soil to stimulate the retention of irrigation water in arable land. It is possible to change the filtering properties of the soil by adding substances to its composition that increase its permeability. Such substances can be, e.g., certain fractions of sand or materials that are not prone to swelling. In this regard, solid mining wastes are of interest (Kostenko et al., 2022b; Kostenko et al., 2024).

The essence of the technology of using fertilisers from coal mine waste is to grind and average the waste heap directly at the place of formation, apply it to the arable surface for pre-sowing cultivation and further incorporate it with a cultivator to a depth of 8–10 cm (Zubova et al., 2012). Such fertilisers do not have a negative impact on the agrochemical state of soils and water resources, significantly increase the biological activity of soils, contributing to an increase in the content of the humic acid fraction in the overall humus balance due to the transformation of organic matter of waste under the influence of weathering processes. At the same time, the ability of the cultivated soils to fix molecular nitrogen from the atmosphere increases by almost an order of magnitude due to the rapid development of free-living nitrogen-fixing bacteria. Under the influence of various doses of carbon fertilisers (up to three t/ha), the specific soil surface increases from 19.87 to 28.18 m^2/g, and the humus content from 1.84 to 2.38%. Having a high sorption capacity, they are able to fix at least 60% of water-soluble organic substances on their surface, while completely absorbing humic acids and 54% of fulvic acids, providing a fairly high degree of their fixation (Zverkovskiy et al., 2006).

The purpose of the research is to substantiate the method and its parameters, which ensures the increase and duration of rain and irrigation water retention in agricultural fields, reducing its losses by evaporation and convective removal.

Soils are considered as a multicomponent system, which includes: mineral particles of different particle size distribution; free, physically and chemically bound water; and gases. The spaces between mineral particles are pores that are partially or completely filled with water or gases. The latter are sometimes combined into cracks. Soils are divided into two groups: loose (coarse gravel and sand) and cohesive (clay). Sandy soils consist mainly of sandy particles, while clay soils contain varying amounts of silt and clay particles. The content of clay particles is (%): in clays – more than 30; loams – 10–30; sandy loams – 3–10; sands – less than 3. Clay soils contain all types of water, including crystallisation, capillary, gravitational and bound water, while sandy soils do not contain bound water. This property determines the peculiarities of water saturation in clay soils compared to sandy soils.

Preliminary visual observations of the distribution of water droplets in the soil in the field showed that they deepen mainly under the influence of gravitational forces; the deepening is accompanied by a decrease in the amount of water in the drop due to the wetting of soil particles along the drop path, as well as spreading to the sides. With an interval of more than a minute, the envelopment of water absorption by the particles and their swelling increases, which leads to inhibition of water seepage. In a simplified form, the mechanism of water migration to the soil is the relatively rapid filtration movement of free water under the influence of gravitational and capillary forces and its subsequent transformation into bound forms available to plants.

Based on the considerations of reducing moisture loss by evaporation, the possibility of mechanisation of its implementation, and minimising the use of additional materials, the authors propose the following technology. To improve the well system, it is proposed to fill the grooves with water, which have a certain width (*a*) and depth

(b) and are located in parallel rows at a distance (c) from each other (Fig. 1). In order to preserve the shape of the groove, it is filled with loose material with high filtration properties, the particles of which are not subject to soaking.

Geometric parameters (a, b, c) are the design parameters of the method, they are implemented mechanically using devices similar to seeders. The hopper of the device is filled with crushed aggregate, e.g., burnt-out rock from waste heaps. This is a cheap mining waste that is accumulated in almost unlimited quantities in mining regions. The crushed waste heap flows from the device's hoppers into the groove, and by filling it, prevents the edges from collapsing (Fig. 2a).

The granulometric composition of the fine mass ensures high moisture transfer and accumulation of irrigation water in the groove and the surrounding soil (Kostenko et al., 2023). The grooves are made with the help of tools in the form of ploughs having a width (a), a working depth (b) and a distance (c) between the ploughs (Fig. 2b). Depending on the chosen parameters of the method, the water content can vary significantly, so the task of the research is to select the rational parameters of the method that ensure

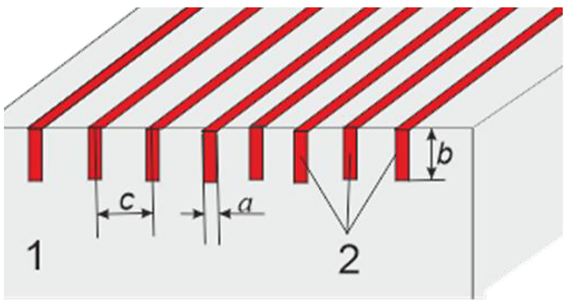


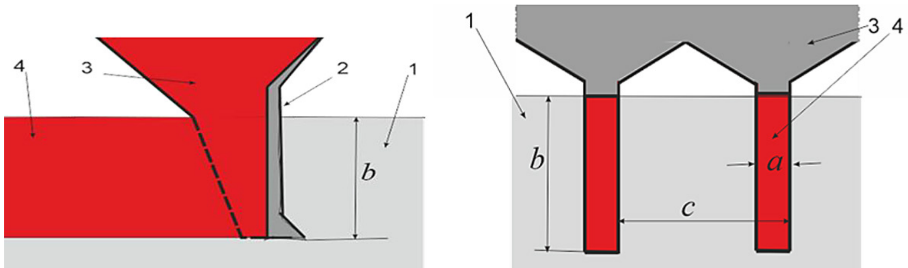
Figure 1. Fragment of arable land (1) with rock-filled grooves (2) for water accumulation: (a, b) width and depth of the groove, respectively; (c) distance between the grooves

the highest water retention in the soil. Based on soil properties and the technical capabilities of agricultural machinery, the probable ranges of the parameters of the water retention method, i.e. the values of a, b, and c, were selected. In the research, it is assumed that the parameters can be, mm: groove width $10 \leq a \leq 200$; groove depth $200 \leq b \leq 300$; distance between the grooves $200 \leq c \leq 400$. These indicators are independent of each other, and therefore each can be chosen arbitrarily. The main task is to substantiate such a correlation between the parameters, at which it is possible to ensure maximum water accumulation.

Based on the assumed primary filtration penetration of water into the grooves, the process of moisture distribution in the soil was studied using computer modelling. For this purpose, a fragment of arable land measuring 2200 × 1500 mm containing four grooves was selected. A 2-D fragment, made using *DesignModeler ANSYS WB* module, is presented in the form of an element mesh using finite elements (Fig. 3). In the areas of contact between soil and rock aggregate, the finite element mesh is more refined in order to obtain the most reliable results during computational studies.

The problem is solved in a non-stationary formulation with a change in position over time. Computational experiments were conducted using *Fluent ANSYS WB* module. For adequate modelling of water flow, its gravitational and hydrostatic pressure in the horizontal direction were taken into account. The Euler model was used to account for the surface wetting of soil particles and rock aggregate. Two phases were considered: air and water. The minimum size of water particles was taken to be $1 \cdot e^{-5}$. The water surface tension coefficient is 0.072 N/m.

Considering the diversity of soils, at this stage of modelling, the main characteristics of the medium are taken as a first approximation. Furthermore, Fluent ANSYS WB module does not take into



(A) (B)

Figure 2. A device for mechanised arrangement of grooves: 1 – arable land; 2 – plough; 3 – hopper with rock aggregate, 4 – filled groove; (a, b) – side and rear views, respectively

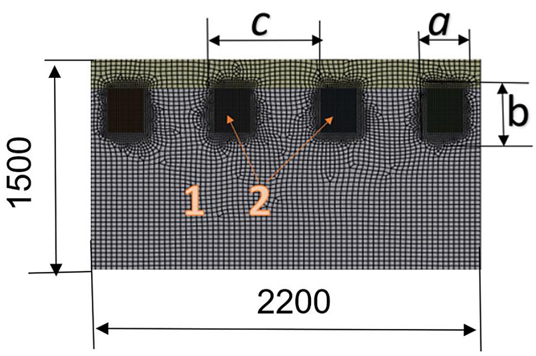


Figure 3. Representation of a fragment of arable land in the form of finite elements, designated as in Figure 1

account the swelling of soil particles when wetted and the dynamics of changes in its permeability. The results obtained in this research reflect the initial period of water penetration into the medium in the filtration mode, which is typical for most types of arable land. In sorption and diffusion processes, which occur at a much slower rate and make it difficult for calcareous soil to further saturate the soil, it is the filtration water that is consumed.

The permeability of water through the soil and aggregate was taken in accordance with Corey Model module, the porosity of the soil was taken as 0.1, it is close to sand in its properties, and the porosity of the rock aggregate is 0.2. The capillary pressure for the aggregate is $1{\cdot}e^{+5}$, and for the soil, it is $1{\cdot}e^{+6}$. Resistance to water penetration through the soil (residual saturation) was taken as 0.05; for rock aggregate, it was 0.0. The main parameters of the modelled media are summarised in Table 1.

Considering the above-mentioned ranges of variation of parameters (a, b, c) of the method of water retention in arable land, we have established possible combinations of them and compiled a matrix of the experimental research plan (Table 2). In accordance with the plan, eight variants of the location of the drainage grooves were modelled. In each model, the dynamics of water distribution was monitored for up to one minute from the start of water supply to the start of colmatation and inhibition of water absorption. As an example (Fig. 4), a visualisation of the dynamics of water accumulation in accordance with the conditions of model No. 3 (a = 100, b = 300, c = 400) is shown.

The example above shows that the water entering the groove moves downwards and sideways under the influence of gravitational forces. The oval-shaped space becomes wetted, where the transition from free to bound forms of water will take place. The location of the bulk of the water in the form of an oval shape below the surface determines its isolation from contact with air and, accordingly, reduces evaporation. The conservation of moisture in the soil for plant nutrition is ensured, i.e. it is theoretically confirmed that the proposed method allows achieving the research purpose.

Table 1. Main indicators of the media used in the modelling

No.	Parameter	Material	Value
1	Porosity	Soil	0.1
		Aggregate	0.2
2	Capillary pressure, Pa	Soil	$1{\cdot}e^{+6}$
		Aggregate	$1{\cdot}e^{+5}$
3	Resistance to water penetration (residual saturation)	Soil	0.05
		Aggregate	0.0

Table 2. Experiment planning matrix, geometric parameters of the grooves (mm)

Model no.	Groove width, a	Groove depth, b	Distance between the rows, c
1	200	300	400
2	200	100	400
3	100	300	400
4	100	100	400
5	200	300	200
6	200	100	200
7	100	100	200
8	100	300	200

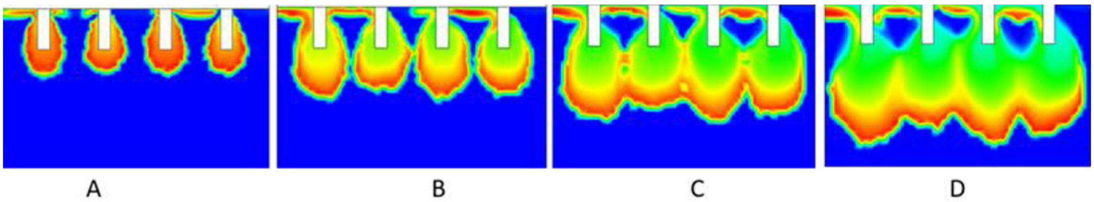


Figure 4. Dynamics of water inflow to the soil, model No. 3: a, b, c, d — time from the beginning of irrigation, respectively, c: 10, 20, 30, 40

RESULTS AND DISCUSSION

We determined the amount of accumulated water at any ratio of the method parameters and to substantiate its rational parameters, namely, the conditions of maximum water content. Within the plane of the selected rectangular fragment (see Fig. 3), the water-wetted part of the surface *Y* (Table 3) was calculated for a time of 40 s, when the filtration movement of water is inhibited and its transition to bound forms begins. The data presented in the table make it possible to draw up a regression equation that allows us to calculate the parameters (*a, b, c*) of the method of water retention in arable land. As a result of the calculations, a multiple regression equation was obtained:

$$Y = 0.01796 + 0.00162a + 0.00114c + 0.00348b \quad (1)$$

Possible interpretation of the model parameters: an increase in *a* by one unit (1 mm) leads to an increase in *Y* by an average of 0.00162%; an increase in *c* by one *mm* leads to an increase in *Y* by an average of 0.00114%; an increase in *b* by one mm leads to an increase in *Y* by an average of 0.00348%. Based on the maximum coefficient β_3 = 0.917, it is concluded that the factor *b* has the greatest influence on the result *Y*.

Table 3. Relative part of the wetted surface of the fragment

Model no.	Fraction of the fragment area, %	
	Grooves	Water-wetted, *Y*
1	3.99	53.82
2	1.49	34.96
3	1.96	53.25
4	0.38	29.43
5	4.85	51.59
6	1.22	27.18
7	0.53	23.84
8	1.7	41.27

The statistical significance of the equation was assessed using the coefficient of determination and Fisher's ratio test. It was found that in the studied situation, 97.63% of the total variability of *Y* is explained by the change in factors (*a, b, c*). The factor *b* (r = 0.9168) has the greatest influence on the effective feature. According to the matrix of paired correlation coefficients, all the coefficients are $|r_к| < 0.7$, which also indicates the absence of multicollinearity of the factors.

The conducted research reflects, first of all, the qualitative indicators of the method – more or less part of the soil will be filled with water under certain parameters of the method of its accumulation. The choice of parameters (*a, b, c*) can be influenced by various circumstances: technical performance of grooving devices; resource life of the rock aggregate; fuel cost restrictions and many others. Therefore, using the obtained regression Equation 1, it is possible to determine the most suitable parameters in specific conditions. The results of the modelling can be used to simultaneously determine the sufficient amount of water and the minimum content of mining waste.

The most accessible and cheapest type of rock aggregate is mining waste in the form of burnt-out waste heaps, but it has disadvantages such as the presence of heavy metals. The use of coal mine waste as a fertiliser increases the biological activity of soils and increases the number of chemical elements necessary for plant growth and development (Żukowska et al., 2023), but their widespread use is limited by the high content of heavy metals in the waste heap, which can accumulate in the green mass of plants. In this regard, there is a need to find ways to reduce the negative impact of heavy metals on plants.

Heavy metals, having high physiological activity and a narrow range of concentration transition from positive to negative effects on living organisms, inhibit their biogenic activity and cause changes in the catalytic activity of enzymes, disrupting the synthesis of vital substances and degrading the quality of plant products. Thus, with an increase in the gross content of lead (Pb) in soils within 21–411 mg/kg, zinc (Zn) – 47...707 mg/kg, cadmium (Cd) – 0.97–6.97 mg/kg, their concentrations in wheat grain increased to 0.45–0.99 mg/kg, 24.7–96.9 mg/kg, 0.076–0.364 mg/kg; the amount of lead and cadmium accumulation in straw was significantly higher than in grain, and zinc, on the contrary, was lower (Savosko, 2016).

One of the additional ways to reduce the negative impact of heavy metals on the quality of agricultural products is to use agricultural methods of extracting heavy metals from soils by growing industrial plants. The cultivation of biofuel plants, such as rapeseed, sunflower, willow etc., reduces the content of heavy metals in the soil and moves them to the stems, leaves, and fruits. The products of such crops are used to make biodiesel, pellets, fuel briquettes, oils, solvents, etc. In some cases, the ash of such fuels can become a raw material for obtaining valuable metals.

CONCLUSIONS

The technology of accumulation and retention of water in arable land is proposed, which consists in arranging parallel rows of grooves of a certain depth and width, which are filled with fine material, mainly mining waste, namely burnt-out waste heaps. The design of a device for implementing the method is proposed taking a seeder as a basis. The most probable parameters of the method, groove width and depth and the distance between the groove rows, are selected in practice.

As a methodology for conducting theoretical studies on the accumulation of irrigation water, computer modelling using *DesignModeler ANSYS WB* module was chosen; a 2-D fragment of arable land measuring 2200 × 1500 mm, containing four grooves, is represented as an element mesh using finite elements.

A matrix for conducting a modelling experiment was developed and modelling experiments on water accumulation were carried out. The problem is solved in a non-stationary formulation with a change in position over time, and computational experiments were conducted using *Fluent ANSYS WB* module.

For the first time, the dependence of water retained in arable land on the parameters of the proposed method was theoretically obtained in the form of a polynomial regression equation. Statistical analysis has confirmed the sufficient reliability and significance of the results.

It is advisable to use the results of the research with sufficient reliability in practice to substantiate the rational parameters of water retention technology in arable land.

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