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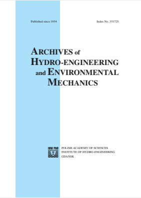

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Formation of a Favorable Filtration Regime of Soils in Saline Areas of the Danube Delta Rice Irrigation Systems

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Abstract. The environmental state of rice irrigation systems (RIS) is determined by many factors, including natural ones (soil, topographical, hydrogeological, and climatic factors) and technological ones (irrigation norm, design, and parameters of irrigation and drainage networks, etc). The most significant influence on the ecological reclamation state of the RIS carries is effected by its drainage network (DN). The need to maintain a flushing water regime with specific filtration rates to prevent secondary salinization in the Danube Delta's rice systems is a crucial aspect of managing these agricultural areas. In the saline areas of rice systems located in the Danube Delta, the DN must ensure the maintenance of the flushing water regime with the rates of filtration ranging between 10 to 12 mm/day. This is a prerequisite for preventing secondary salinization of irrigated lands of these rice systems. According to the results of studies, the filtration from the surface of the irrigation checks of the Danube Delta RIS has been established, and its values in the area of the rice check vary significantly. Different intensity of filtration in the area of rice checks causes the difference in mineralization of groundwater and in the content of salts in the soil. This leads to the fact that the same rice check created various natural reclamation conditions and different productivity of cultivated crops.

Key words: vertical filtration, ecological-reclamation state, rice irrigation system, drainage network

1. Introduction

Rice holds significant importance as a staple grain for humanity. Annually, global rice production reaches approximately 500 million tons, and over half of the Earth's population consumes this cereal thrice daily. (Li 1999, Monaco, Sali G. 2018, Pandey et al 2010, Katambara et al 2014).

Regarding cultivated land and total grain harvest, rice is the second-largest crop globally, following wheat. In certain years, the overall rice harvest surpasses that of

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wheat, thanks to its high yield. (Bouman, Tuong 2001, Bouman et al 2006, Fang, Zhang 1996, Reuben et al 2016, Mannocchi, Mecarelli 1994, Tuong, Bhuiyan 1999, Prykhodko et al 2023, W. Di 2017).

Rice stands alone among grain crops in its ability to sustain a substantial portion of the population in tropical countries. Unlike wheat and other grains, which yield poorly in the humid monsoon conditions typical of tropical climates due to susceptibility to rust damage, rice remains unaffected and produces significant yields. Additionally, during the rainy season when vast areas of river valleys are flooded, only rice can thrive, seemingly designated by nature for cultivation in such environments. These lands become fertile for rice farming during this period, while in the dry season, they remain infertile due to water scarcity. However, with artificial irrigation, multiple rice crops can be cultivated in these areas each year.

Since most of the rice irrigation systems (RIS) of the Danube Delta, are built on previously salted areas territories with a close occurrence of low-flow mineralized groundwater, then the reduction of the share of flooded rice in crop rotations created ideal conditions for further expansion of areas of secondary salinization and salinization of irrigated areas of land, which can put rice systems on the brink of ecological disaster.

The ecological-reclamation condition of rice irrigation systems depends on various factors, encompassing natural elements such as soil, topography, hydrogeology, and climate, as well as technological factors like irrigation norms, design, and parameters of irrigation and drainage networks. The decline in the ecological-reclamation state of irrigated lands has emerged as the primary cause of reduced yields in both rice and the associated crops in rice crop rotations. A pivotal role in shaping the ecological-reclamation state of RIS is played by the drainage network (DN). The DN in rice systems stands out as a critical component, serving the purpose of discharging surface water from the rice fields and regulating groundwater levels throughout various stages of rice vegetation and the growth cycles of accompanying crops in the rice rotation. In the saline lands of rice systems in the Danube Delta, the DN serves as the principal means of active and targeted influence on the water-salt regime of the reclaimed territory and the groundwater regime during the growing season and periods between irrigations. Essentially, the efficiency of the DN becomes the decisive factor in determining the productivity of agricultural lands.

The purpose of this research is to identify the causes of deterioration of the ecological-reclamation state of rice irrigation systems and to develop integrated system solutions to improve it.

2. Methods and Techniques

The research was conducted at the Kilia Rice Irrigation System (RIS) in the Odesa region, Ukraine, as illustrated in Figure 1, spanning the years 2003–2021. Commonly accepted methods, including the application of water and salt balances, were employed as standard tools to evaluate and predict the ecological and reclamation conditions of the RIS. The investigation utilized an information base comprising source data for the specified object, spanning the period from 1966 to 2021, encompassing the entire operational history of this RIS.

Fig. 1. Location of the study area

The Kilia RIS covers a total area of 3.45 thousand hectares. The soils within the Kilia RIS are characterized by a light granulometric composition, predominantly sandy loam, extending to the first regional water confining layer.

Before the establishment of the Kilia RIS, the groundwater level ranged from 0.0 to 2.5 meters in depth, with a general slope toward the Danube River. The salt content in groundwater varied between 10 and 30 g/l, reaching up to 70 g/l in specific instances. The mineralization of groundwater increased from the swampy part of the floodplain to its central section. Over an extended period of rice cultivation on the Kilia RIS, desalination of groundwater occurred, with mineralization decreasing to 1.5–15 g/l. This reduction is attributed to the relatively intense washing regime resulting from rice irrigation through flooding and drainage activities. In small areas, there was even desalinization of groundwater to levels as low as 30 g/l.

The design of the Kilia RIS followed the well-established method of irrigation of the Krasnodar type (Fig. 2), as outlined by Oliynyk (1981), Rokochinsky et al

(2015), and Stashuk et al (2016), including rice checks for the wide front of flooding and water discharge with one-sided and two-sided commands (Rokochinsky et al 2014, 2016, 2023, Zhovtonog 1984). The distance between canals, depending on soil-hydrogeological conditions, ranges from 200 to 500 meters, and the depth of drainage is set at 1.5 to 1.7 meters.

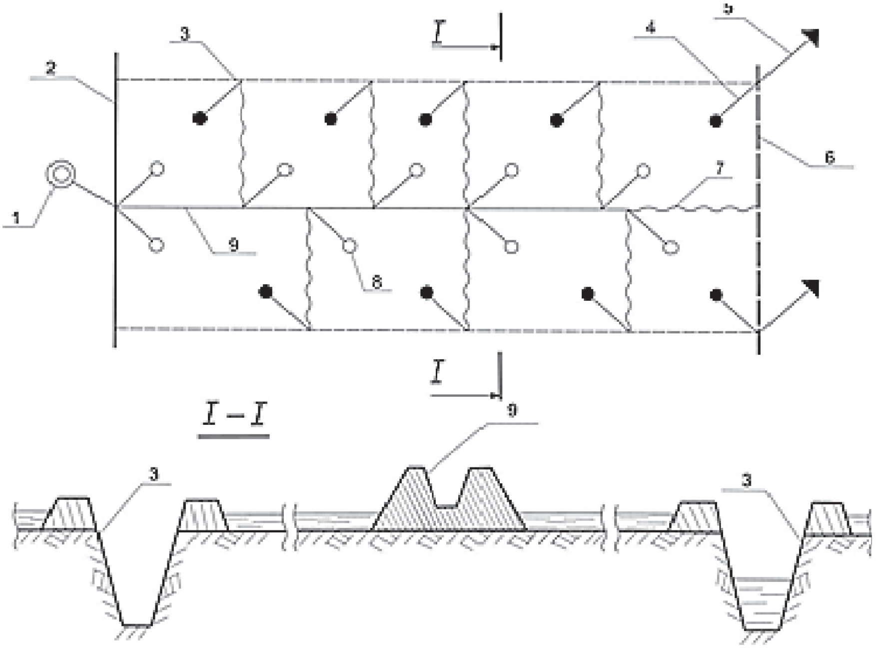

Fig. 2. Scheme of the irrigation method of the Krasnodar type: 1 – water discharge from the distribution irrigation canal to the irrigation canal; 2 – distribution irrigation canal; 3 – drainage and discharge canal; 4 – water release from the check to the discharge; 5 – water discharge from the drainage and discharge canal into the site discharge; 6 – area reset; 7 – check roller; 8 – water discharge from the irrigation canal into the check; 9 – irrigation canal

3. Results and Discussion

The operational experience of the Kilia RIS underscores that the ecological reclamation condition is contingent on the effective functioning of all components of the rice system, with particular emphasis on the DN. Extensive research over an extended period has identified essential requirements for drainage on saline lands within the RIS:

- Ensure, over 2–3 years, salinization of the upper soil layer to a depth of 1.0 to 1.5 meters, establishing favorable conditions for the cultivation of rice and the associated crops in the rice rotation;
- After draining water from the rice checks, sustain the necessary drainage level, not falling below the critical depth of 1.5 to 1.8 meters, at the commencement of the new irrigation season;
- Preclude the occurrence of secondary salinization in fields occupied by accompanying crops, ensuring their sustained productivity;
- Establish and uphold optimal filtration rates within the rice field to facilitate the removal of salts from the active soil layer.

Adhering to these fundamental requirements is crucial for sustaining the ecological reclamation state of the Kilia RIS and optimizing conditions for successful rice cultivation and associated crops.

The assessment of the drainage system's effectiveness in the rice system, as outlined by Goncharov (1969), Mendus et al (2007), and Turchenuk et al (2016), revealed that the drainage implemented in the 1960s, following the design standards of that era, falls short of providing adequate drainage for rice fields. This inadequacy stands as a significant factor contributing to the unsatisfactory ecological reclamation state and the decline in yields of both rice and the associated crops in the rice rotation.

Over the prolonged use of the DN in these systems, numerous factors have led to substantial deformations (Korobiichuk et al 2017, Kuzmych et al 2021, Kuzmych, Voropai 2023, Kuzmych, Yakymchuk 2022, Turchenuk et al 2022). The shallow drainage canals (1.2 to 1.5 meters) fail to deliver the necessary drainage and aeration to the upper soil layers, particularly between irrigation periods. In the absence of sufficient drainage, the water saturation of the soils in the aeration zone significantly rises, giving rise to the accumulation of toxic substances for rice (hydrogen sulfide, methane, iron oxide, among others). This, in turn, reduces the activity of organic substance decomposition and increases soil alkalinity. The diminished fertility of the soils hampers rice development, thereby negatively impacting the overall effectiveness of rice cultivation and the associated crops in the rice rotation.

Simultaneously, the degree of drainage in the rice field is determined by the rates of vertical filtration established on it. Research on filtration from the surface of the irrigation methods of the rice system, as conducted by Mendus et al (2007), Peng et al (1994), and Cesari de Maria et al (2016), indicates that the most substantial values of filtration (ranging from 4 to 20 mm/day) are observed in the designated drainage zones, situated up to 50 meters from the drains. These rates depend on the water levels in drainage canals and the corresponding pressure gradient. Moving closer to the midpoint between the drainage canals, irrespective of the design of irrigation methods and the spacing between drainage canals, the filtration rate ranges from 1 to 2 mm/day, practically approaching absence (Fig. 3, 4).

At the same time, the maximum values of rates of vertical filtration (25–30 mm/day) are observed during the period of the initial flooding of the checks, and then

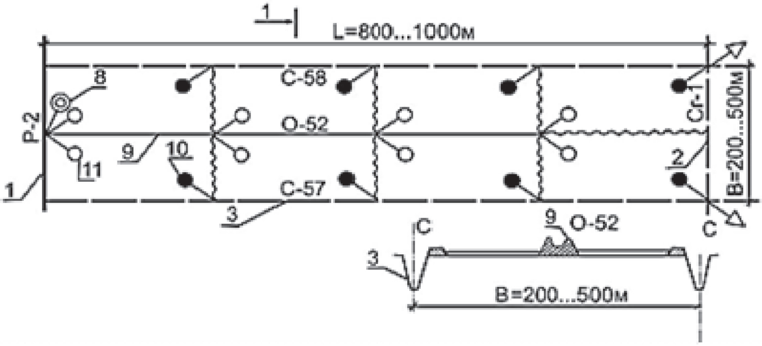

Fig. 3. Chart of the rice check with water drainage of Krasnodar type of the Danube RIS:
1 – distribution canal; 2 – water discharge canal; 3 – field drain or discharge drain; 4 – one-side irrigation and discharge canal; 5 – water discharge from the distribution canal to the irrigation drain; 6 – water discharge from the irrigation system to the discharge canal; 7 – water drainage from the field drain into the drainage canal; 8 – water discharge from the distribution canal to the check irrigation; 9 – check irrigation; 10 – water discharge from the check to the drainage canal; 11 – water discharge from the irrigator to the check

through saturation of the soil and the rise of groundwater levels gradually decrease to 1–2 mm/day (Fig. 5).

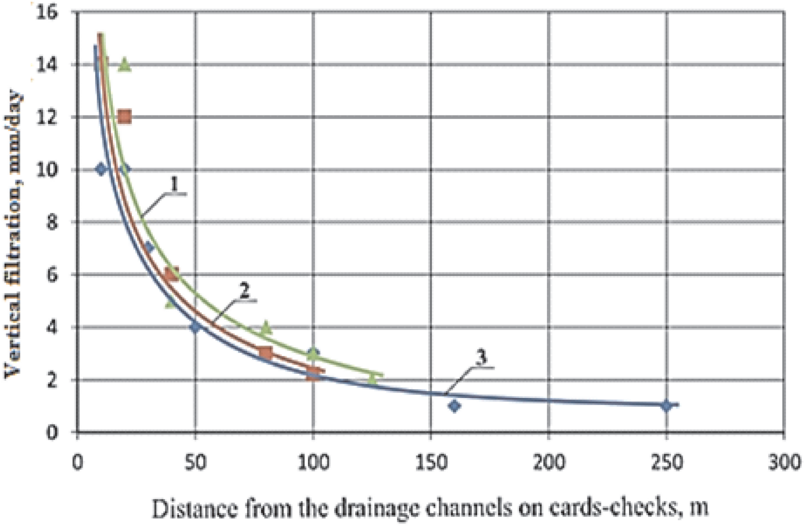

Fig. 4. The rate of vertical filtration at the checks, depending on the distance between the drainage canals *B*:
1 – B = 200 m, 2 – B = 250 m, 3 – B = 500 m

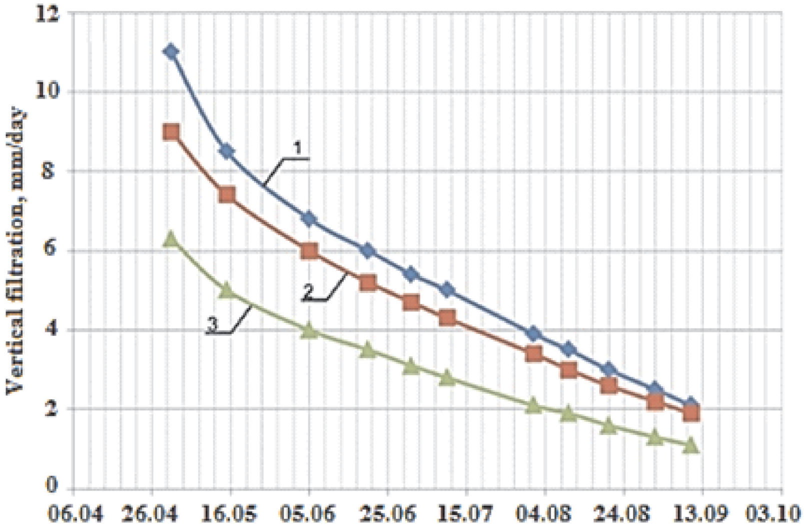

Fig. 5. Dynamics of vertical filtration during the growing season of rice: 1 – light loamy soils, 2 – medium loamy soils, 3 – heavy loamy soils

The varying intensity of filtration across the width of the checks results in a significant disparity in groundwater mineralization and soil salt content. This discrepancy gives rise to distinct natural-meliorative conditions within the same check and, consequently, varying productivity of cultivated crops.

Field investigations conducted by our team and other researchers (Turchenuk et al 2016, 2017) in the rice systems of the Danube Delta reveal specific characteristics in the flow of filtration streams on irrigation cards during the maintenance of the water layer. A zone of groundwater buckling is formed along the irrigation canals, and a stagnant zone develops in the center of the check. Active groundwater movement occurs only in the part of the area directly adjacent to the drainage canal (Fig. 6).

The dimensions of these zones are influenced by the hypsometric characteristics of the irrigation channels, the depth of drains and water levels in them, and the size of the irrigation check.

The presence of such zones indicates irregular drainage across the area of the irrigation check, with more than 60% of the practical area not draining. Calculations of filtration losses from the drainage zone, based on the rate schedule, indicate that their volume from the drained strip comprises about 70% of their total volume. Given that filtration from rice fields constitutes almost half of the irrigation norm, reducing filtration losses stands as a primary approach to diminishing its overall value and the total volumes of water intake and drainage for rice cultivation. In assessing the overall filtration value, it's noteworthy that it varies widely, ranging from 8300 m^3/ha to 12000 m^3/ha, contingent on the design of irrigation checks and drainage parameters. This value accounts for up to 50% of the consumable portion of the water balance.

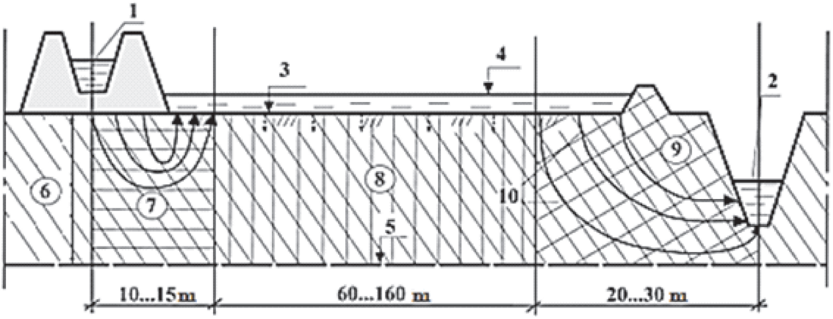

Fig. 6. Scheme of formation of characteristic zones of filtration on the profile of the rice check:
1 – irrigation canal; 2 – drainage canal; 3 – the surface of the soil; 4 – water surface; 5 – boundary of the estimated layer of soil; 6 – estimated layer of soil; 7 – zone of buckling of groundwater; 8 – stagnant zone; 9 – zone of active filtration; 10 – lines of direction of movement of filtration streams

In our analysis, which is grounded in both our findings and the outcomes of previous filtration studies (Turchenuk et al 2016, 2017), we propose that, for the establishment of favorable water-air and salt regimes in the soils of the aeration zone during the rice growing season, the intensity of filtration should be moderately low and consistent across the irrigation check area. Moreover, the filtration process should be actively managed.

In light of this, we can infer that during the rice growing season, the rate of vertical filtration in the upper soil layer within the entire rice check area should be maintained within the range of 10 to 12 mm/day (Turchenuk et al 2016, 2017). However, achieving uniform drainage across the entire rice field under the current designs of rice cards and drainage parameters is deemed unattainable.

Given the constraints of not being able to alter the type, structure, and parameters of drainage without reconstruction, the sole factor that can be controlled to manage the natural reclamation regime under the operational conditions of existing rice irrigation systems is the water regulation process. This process is shaped by the ratio of the amount of water supplied to the system to the amount of water drained outside the system.

The rate of vertical filtration in the rice field can be influenced by adjusting the water levels in the DN and the volume of water supplied to the field (Turchenuk et al 2017). Since the inflow of filtration in drainage canals is contingent on the water permeability of soils and the pressure gradient of the filtration flow, an important factor affecting its value is the depth of filling in drainage canals and the water level regime in them throughout the year. Altering the depth of filling in drainage canals enables the regulation of filtration water inflow from flooded rice checks. Maintaining water levels in drainage canals reduces the rate of filtration (4 to 5 mm/day in the drain zone), and it practically diminishes to zero with increasing distance from the canal. Therefore, by controlling water levels in the DN and on the surface of the rice field, the rate of filtration from flooded rice checks can be adjusted, leading to a significant reduction in water loss through filtration (Fig. 7).

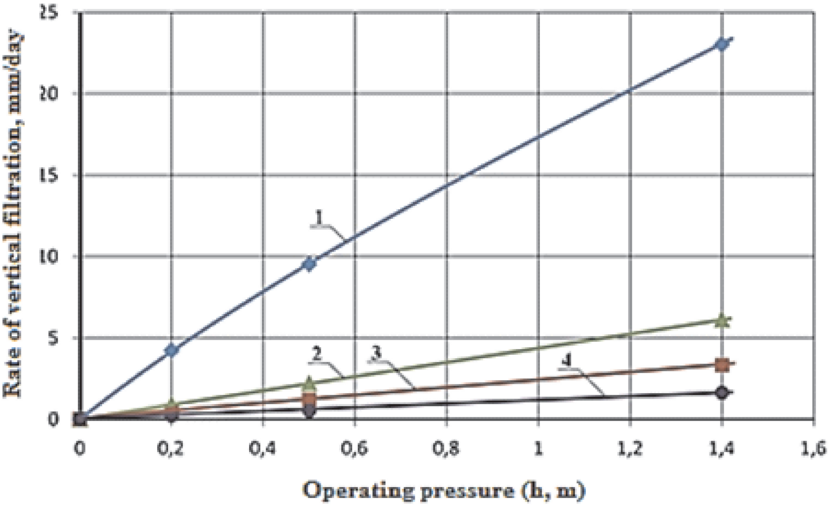

Fig. 7. The rate of filtration from the surface of the rice field depending on the value of operating pressure and the distance from the axle of the drainage canal (distance between the drains is 200 m):
1 – 15 m, 2 – 35 m, 3 – 50 m, 4 – 100 m

As depicted in Fig. 5, the rate of filtration from the check-in zone influenced by the drainage canal, with varying parameters of the DN and free flow of drainage water (h = 1.5 m), ranges from 20 to 25 m/day. When the water level is maintained (h = 0.15 m), the rate of filtration decreases to 2 to 5 mm/day. Overall, the rate of filtration across the check fluctuates from 8 to 12 mm/day to 3 to 5 mm/day, contingent on the parameters of the DN. Establishing a supported water level in drainage canals allows a reduction in both the irrigation norm to 18,795 m^3/ha and the filtration discharges into the DN to 7,732 m^3/ha, thereby decreasing the costs associated with water pumping by pumping stations.

Maintaining supported water levels should be implemented in card drainage canals located within the rice field from the re-flooding of rice fields after germination until the rice reaches maturity. The establishment of a supported water level is crucial not only for reducing filtration losses but also for enhancing the stability of drainage canals (Turchenuk et al 2016).

Based on measurements of drainage runoff at different depths of drainage canal filling, a relationship between specific drainage runoff and operating pressure was identified, as illustrated in Fig. 8. This relationship can be approximated by the following equation:

$$q = 2.57h^{1.7}, \tag{1}$$

where q is the specific drainage runoff from the drainage canal (l/s from 1 km of a canal length, and h is operating pressure, in metres.

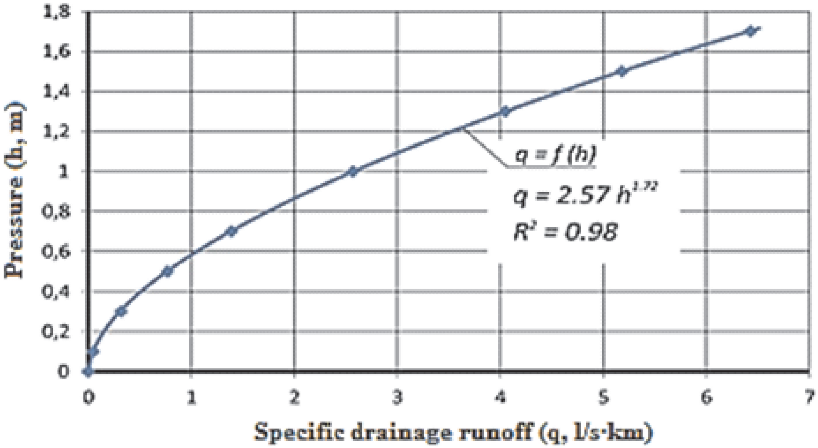

Fig. 8. Dependence of drainage runoff from the card drainage canal on the operating pressure

In field experiments conducted at the Kilia RIS, the specific drainage runoff from the card drainage canals at an operating pressure of h = 1.7 m was measured at 6.43 l/s·km. Contrastingly, at a lower pressure of h = 0.3 m, the specific drainage runoff dropped significantly to 0.32 l/s·km, marking a reduction of almost 20 times. This underscores the potential for achieving substantial reductions in water losses from flooded rice checks by diminishing the operating pressure through the establishment of supported water levels in drainage canals during the growing season.

The implementation of a more favorable water-salt regime and the enhancement of the chemical composition of irrigated soils in rice systems, achieved through increased salt removal by filtration, positively impact crop yields. In the case of seeding at a rate of 710 seeds per 1 m^2 (using the rice variety “Vikont”), the rice germination density reaches different levels depending on the average filtration rate: 183 pcs/m^2 at up to 10 mm/day; 213 pcs/m^2 at 10–15 mm/day; 202 pcs/m^2 at 15–20 mm/day, and 187 pcs/m^2 at 20 mm/day (Table 1).

It was observed that in areas with insignificant filtration rates, known as stagnant zones, the rice yield was smaller. Higher rice yields were recorded in check areas located approximately 60 meters from the drain, where the average filtration rate in the upper soil layer ranged from 0.005 to 0.015 m/day. Deviating from these values,

Table 1. Influence of filtration from the rice check on the germination the density of rice plants

Average filtration rate, mm/day	Number of sown seeds, pcs	Number of of rice plants per 1 m^2			
		during germi-nation	% of sown	in the period of full stairs before tillering stage	% thinness stairs
< 10	710	205	28.9	183	10.7
10–15	710	218	30.7	213	2.3
15–20	710	213	30.0	202	5.2
> 20	710	204	28.7	187	8.3

either higher or lower, resulted in lower rice yields. For instance, at a distance of 10 meters from the drain with a filtration rate of 25 mm/day, the rice yield was 48 center/ha; at a distance of 40 to 50 meters, where the filtration rate decreased to 12 mm/day, the yield was 71 center/ha; and at a distance of 100 meters, with a filtration rate dropping to 4 mm/day, the yield was 52 center/ha (Fig. 9).

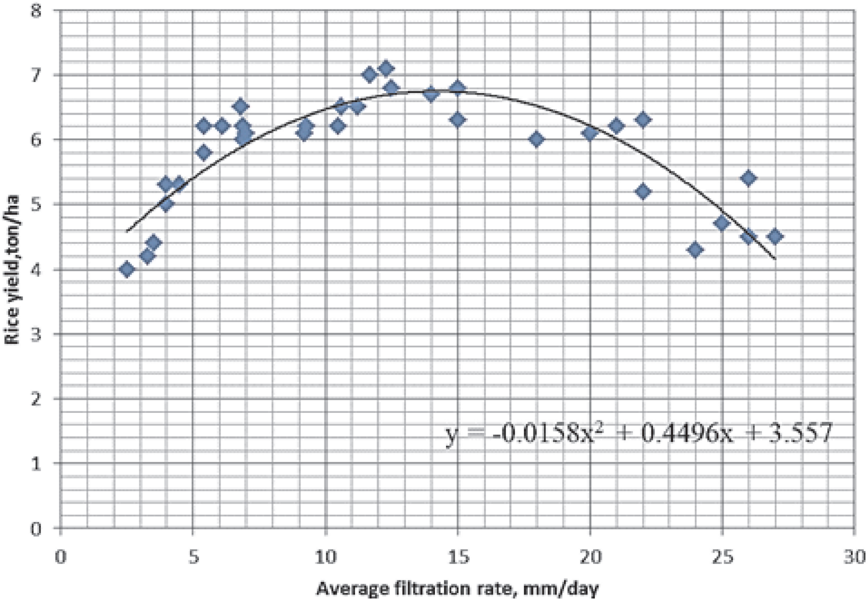

Fig. 9. Dependence of rice yield on the rate of filtration from the check surface during the growing season

The investigation revealed that in areas characterized by an insignificant filtration rate, known as stagnant zones, the rice yield was notably smaller. In contrast, higher rice yields were observed in check areas located approximately 60 meters from the drain, where the average filtration rate in the upper soil layer ranged from 0.005 to

0.015 m/day. Deviating from these values, either higher or lower, resulted in lower rice yields. For instance:

- at a distance of 10 meters from the drain, with a filtration rate of 25 mm/day, the rice yield was 4.8 ton/ha;
- at a distance of 40 to 50 meters, where the filtration rate decreased to 12 mm/day, the yield increased to 7.1 ton/ha;
- at a distance of 100 meters, with a filtration rate dropping to 4 mm/day, the yield was 5.2 ton/ha (Fig. 9).

4. Conclusions

The effective functioning of the DN in rice systems is contingent upon the proper selection of its parameters, specifically the distance between drains and the depth of their installation. These parameter values should be calculated to create optimal conditions for cultivating accompanying crops, with a primary focus on preventing secondary salinization. To enhance the ecological reclamation state of irrigated lands, increase rice yields, foster favorable conditions for oxidation-reducing processes, and eliminate the potential for secondary salinization, it is an imperative to ensure the required level of infiltration of irrigation water beneath the rice field. Additionally, uniform distribution of water across the rice check card’s surface is crucial.

During the rice growing season, maintaining vertical filtration rates in the upper soil layer within the range of 10 to 12 mm/day is essential. Such filtration rates contribute to achieving the highest yields of rice and accompanying crops while preserving the proper ecological reclamation state of irrigated lands. Adjusting the values of vertical filtration rates in the rice field can be achieved by controlling the water levels in the drainage network. Filtration rates within the range of 12 to 15 mm/day at appropriate stages of rice vegetation ensure the removal of salts from the soil without leaching soil nutrients. This approach provides a balanced solution for optimizing rice cultivation and maintaining the health of irrigated lands.

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