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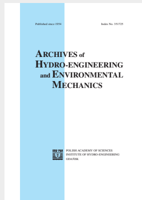

Justification of Technological and Design Parameters of Polder Drainage Systems by an Optimization Approach

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Abstract. A system optimization method was used, which consists in the consistent justification of optimal technological and constructive solutions and parameters of drainage polder systems during the development of their projects. This is done in compliance with modern economic and environmental requirements according to criteria and models for different levels of management decision-making over time (project, planned operation). Based on the performed relevant predictive and optimization calculations for the conditions of the real object, the following three tasks have been accomplished. (1) The optimal pump module at the stage of operation for the existing polder drainage system has been substantiated. (2) The design of the pumping unit and the parameters of its components during the reconstruction of the polder drainage system have been improved. This made it possible to reduce the load on the pumping equipment, the duration of its operation, and the cost of electricity by 20–40%, depending on the water level of the year. The improvement was carried out by the diversion of the corresponding part of the surface runoff with additionally introduced gravity elements in the form of a puncture in the body of the protective dam and a siphon intake. (3) We have substantiated the optimal water regulation technology for the existing polder drainage system in modern and forecast weather and climate conditions, which will ensure the maintenance of the necessary water-air regime of the drained soils in different phases of the growing season of agricultural crops. This will make it possible, on demand, to increase the energy and general environmental and economic efficiency during their creation and functioning of the polder drainage system in accordance with modern changing conditions.

Key words: polder drainage system, technological and constructive parameters, ecological, economic and investment evaluation

1. Introduction

Because over the past two decades, as a result of the transition of the country's economy to a market economy, when the financing of the maintenance of land reclamation facilities was rather low, in the conditions of climate change, the operation efficiency of both polder drainage systems (PDS) and reclamation drainage systems (DS) as a whole has decreased. That's why most of them are in an unsatisfactory technical and ecological state. In the territory of the Western Polissia of Ukraine, the area of drained land is 1232.4 thousand ha. At the same time, the area where (PDS) with reliable mechanical drainage were built is 96.7 thousand hectares.

In the past design decisions for the constructing of polder drainage systems were characterized by the following features:

– overestimated reliability, which affected the overestimated cost of construction works of this type of objects (the design economic efficiency of the vast majority of such objects was actually not achieved);
– the ecological component was actually not considered and taken into account during the construction of such water management and reclamation systems, and their ecological and reclamation status was mostly unsatisfactory;
– the low energy cost was not a limiting factor in their construction and operation. Currently, the existing PDS are subject to the following changes in the conditions of their operation:
– a significant increase in energy cost;
– significant wear and tear of pumping and power equipment and other technical elements of the system, silting of reclamation canals and the collector and drainage network, unsatisfactory technical condition of hydrotechnical structures on reclamation systems, etc.);
– violations in design parameters and a decrease in both the technological (ameliorative) and agricultural efficiency of reclaimed lands (decrease in their productivity by 25–50% compared to the design one) (Shumakov 1996);
– emergence of environmental problems (flooding of agricultural lands, increased washing regime of drained soils);
– low level of agricultural production and use of drained polder lands;
– unsatisfactory ecological and reclamation status of drained polder lands, etc. (Aydarov et al 1990).

Therefore, today the issue of increasing the overall technological, ecological and economic efficiency of drainage, primarily polder systems operation, is extremely important. This will make it possible to:
– improve the technological and technical condition of the polder system;
– improve water regulation regimes and technology, as well as the operation of the polder pumping station;
– increase the fire safety of drained peat soils;
– forecast of changes in their ecological and meliorational status for the nearest and distant perspective, taking into account changes in weather and climate conditions.

Polder systems are an extremely complex and specific object of research in terms of their construction and functioning, compared to other traditional drainage systems. That is why we adopted a systematic approach and system analysis with its integral component – the method of optimization and modeling of complex objects and systems as the methodological basis for solving the specified problem. Such complexity of the problem requires developing and applying modern optimization methods. Such methods are aimed at more complete relationships and interactions of production and natural processes during the functioning of PDS that can be solved by a complex optimization problem with heterogeneous elements.

Therefore, to ensure the effective development of the agricultural sector of the economy of Ukraine, it is necessary to restore the productivity and resource potential of water management and reclamation facilities. This is impossible without increasing the overall technical, technological, economic and environmental efficiency of their construction and operation in accordance with current changing conditions and requirements. As a result of climate change, existing environmental problems become more complicated and require the coordination of economic and environmental goals, which achieve the necessary overall ecological and economic effect (Kovalenko et al 2021, Orlinska et al 2022, Kuzmych, Voropai 2023).

Thus, the purpose of the presented research is the consistent substantiation of the optimal technological parameters of polder drainage systems (pumping module and water regulation technology) and structural parameters (pumping node design) based on the application of a method of system optimization. This system optimization consists of finding intermediate local optima, when each subsequent optimal decision is made by taking into account the previous one in the sequence.

2. Methods and Techniques

Currently, in the drainage area, polder drainage systems with mechanical water lifting are the most technically advanced. Such systems have indisputable advantages over gravity ones both in terms of efficiency of regulating the water regime and ecology. The main disadvantage of PDS is the relatively high cost of their construction and operation. However, on the path of technical improvement of drainage systems, the future is for systems with mechanical water lifting. And in the conditions of periodic land flooding, there is no alternative to polder drainage, which is already quite developed, both in Ukraine and in the countries of Eastern and Western Europe (Schultz 2008).

The need for additional irrigation of drained lands in the western Polissia was proven by the researches of Dolid (1990) and other scientists. At the same time, as it was noted by (Dolid 1990, Kovalenko 2011) PDS are quite convenient hydrotechnical complexes in terms of two-way regulation of the water regime. Due to them in certain periods it is possible to achieve the desired groundwater level in the fields by changing the mode of water pumping by the pumping station and timely closing of the shields of the sluices-regulators.

The issue of regulating the water regime of drained lands on the PS in different natural and climatic zones was studied only in certain areas. In particular (Alfonso et al 2010, Van Overloop 2006) considered the optimization of water levels on such systems. These traditional methods and research of a high scientific level made it possible to develop appropriate practical recommendations for the design and operation of the PDS.

When designing PDS, an important element of their calculation is the total flow of water to the PS (pumping station) (pumping module). Depending on its value, both the total consumption of the PS and the number and consumption of individual pumping units are determined. But, as evidenced by practice and the accumulated experience of the long-term operation of such objects, the PS parameters calculated according to simplified approaches (for example, the pumping module was recommended to be considered and accepted only from the design area of the polder practically without taking into account multiple other determining factors of influence) considered only the technological efficiency PDS, practically without taking into account their economic and ecological efficiency, which is a mandatory condition.

Therefore, in the 70s of the last century, the need to change scientific and methodical approaches to the creation and functioning of water management and reclamation facilities based on the application of the optimization method was scientifically substantiated.

Generalized conceptual approaches to the optimization of the reclamation regime through the formulation of general principles and the definition of indicators, criteria and the creation of optimization models are considered in the recommendations of I. P. Aidarova, O. I. Holovanova, Yu. M. Nikolskoho, L. M. Reksa, and others. The main provisions of these recommendations regarding the zone of drainage reclamation, together with other similar developments, are taken by us as the basis of the conducted research (Handbook…2023).

According to the studies carried out at that time (K. T. Khommik, I. S. Rabochev, I. V. Minaiev, L. A. Downey, J. Doorenbos, A. H. Kassam, M. O. Lazarchuk, etc.), the economic-mathematical method, which combines the advantages of traditional hydromechanical and empirical methods and is based on the implementation of a complex of predictive and optimization calculations, was adopted to determine the parameters of reclamation systems and their modes of operation. But the optimization methods and models developed at that time were considered and used mainly for the justification of local single decisions regarding individual elements of the system or water regulation technologies, in particular, the optimal parameters of the main channel, hydrotechnical structures, drainage, etc.

At the same time, it turned out that in the modern conditions of the transition to market relations in the country, this method, as a simplified optimization method, in the form in which it was implemented, considered only the economic component of optimization and did not take into account environmental efficiency when determining optimal technical and technological solutions and their parameters. It also does not meet modern requirements, namely:

– insecurity of comparison of options for project solutions in terms of the volume and quality of the obtained agricultural products;
– conditionalities and the relevant relativity of the implementation of this method regarding the term of determination of productivity losses and the validity of the design values of this productivity;
– impossibility to differentially determine the optimal parameters of technical and technological solutions for water regulation about different levels of productivity of cultivated crops, taking into account the multiple variables of the natural-agro-reclamation conditions of the real object;
– non-compliance with modern ecological and economic requirements.

That is why the existing methods of design and calculation of PDS need to be changed and transition to a system methodology for determining their energy efficiency and overall efficiency of operation.

Consideration of a PDS as a complex natural-technical and ecological-economic system requires finding the general optimum in such a system on the basis of system optimization. The essence of such optimization consists in finding intermediate and local optima for all its main components of water regulation elements (pumping station, main canal, sluices-regulators, drainage, etc.) and their operation modes (pumping and water supply units, etc.), by all the main variables in space and time factors affecting the efficiency of water regulation (climate, topography, cultivated crops, soils, schemes and technology of water regulation, etc.) (Volk 2023). The same applies to the search for the optimum also for all components of the system *effect – mode – technology – construction design* and the implementation of the proper optimization model (Volk, Haponiuk 2023).

By analogy and in the development of such an approach, in accordance with the structural scheme of the PDS (Fig. 1), it is advisable to consider the technical subsystem of the type of *parameters of water regulation (pumping) ⇔ parameters of embankment dams ⇔ parameters of a closed collector and drainage network ⇔ parameters of reclamation channels, regulating structures and advance camera (regulating basin) ⇔ parameters of pumping and power equipment*, etc.

The flow of water from the surface of the reclaimed field through all elements of the PDS is created due to the pressure gradient in the advance chamber (regulating basin), which is ensured by the operation of the PS and, accordingly, the amount of electricity spent on it, which determines the significant energy consumption of this process.

Thus, the optimization of the parameters of various efficiency indicators of the primary reclamation measures on the existing PDS can be presented as *given parameters of the economic and ecological effect ⇔ the optimal pumping modules ⇔ the optimal parameters of the PDS*.

At the same time, the pumping module acts as a key link of such a subsystem, as the main factor providing water regulation. Then, the functional connection between its components determines the need to use system optimization. This is when differ-

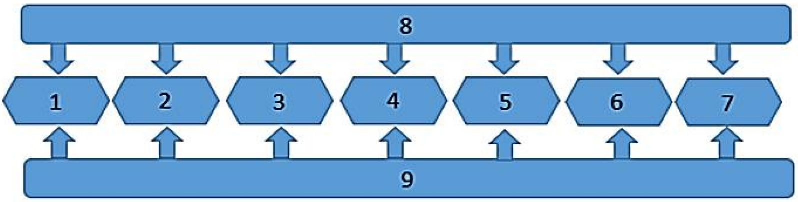

Fig. 1. Structure diagram of PDS
1 – embankment dams; 2 – collector and drainage network; 3 – a network of side channels; 4 – the main channel; 5 – advance chamber or regulating pool; 6 – pumping and power equipment; 7 – water intake; 8 – regulating structures and means of automation of drainage; 9 – regulatory structures and means of automating water supply

ent levels of decision-making are consistently considered in time by various criteria regarding the optimization of pumping module parameters, which are used to justify the design parameters of the PS and other elements of the PDS in their relationship.

Thus, the substantiation of the technological and design parameters of the PDS based on system optimization includes the performance of optimization calculations in the following sequence: substantiation of the optimal pumping module at the stage of operation for the PDS; substantiation of the design of the pumping unit and the parameters of its components during reconstruction; substantiation of the technology of water regulation of drained lands for PDS. This is possible under appropriate criteria, conditions, and complex models of economic and environmental optimization regarding different levels of management decision-making over time (project, planned operation, operational management of the object).

At the operation stage of the existing PDS, by analogy with (Rokochinskiy et al 2023), the optimal parameters of the pumping module can be justified by the following complex optimization model

$$\begin{cases} D_0 = \max\limits_{\{i\}} \sum\limits_{n=1}^{n_p} D_{ip} \cdot \alpha_p, \quad i = \overline{1, n_i}; \\ q_0 = \min\limits_{\{i\}} \sum\limits_{n=1}^{n_p} D_{ip} \left| q_s - \hat{q}_{ecol} \right| \cdot \alpha_p, \quad i = \overline{1, n_i}, \end{cases} \tag{1}$$

where D_0 – is the optimal value of the criterion of net income D by the i-th variant of PD population $\{i\}$, $i = \overline{1, n_i}$, UAH/ha; α_p is known (determined or specified) values of repeatability or shares of the possible state of typical meteorological regimes in the estimated vegetation periods of the population $\{p\}$, $p = \overline{1, n_p}$ within the design term of the object's operation, $\sum\limits_{p=1}^{n_p} \alpha_p = 1$; q_0 – is the optimal estimated value of the drainage coefficient by the i-th version of the PD, l/s·ha; (the optimal calculated value of the drainage flow module according to the i-th variant of the design solution, as the conditions for the environmental optimality of the pumping module for the PDS, l/s·ha); q_s – is the weighted average value of the drainage coefficient within the system and the design term of the object's operation by the i-th version of the PD, l/s·ha; $\hat{q}_{ecol}$ – is the limit value of the drainage coefficient, which corresponds to the level of ecological efficiency of the drainage operation in the studied conditions, l/s·ha; i – is the variants of the PD population $\{i\}$, $i = \overline{1, n_i}$ regarding the type, design and drainage parameters.

The economic criterion for optimization is the indicator of *net income D*. Net income is achieved by obtaining a certain volume of agricultural products grown on reclaimed lands when applying various options for technological solutions of the population $\{i\}$, $i = \overline{1, n_i}$ – possible methods and schemes of water regulation at the system, determined by its type, design, water supply, etc. (Volk et al 2022).

$$D_i = V_i - C_1, \quad i = \overline{1, n_i}. \tag{2}$$

In this case, the optimization condition is the maximization of the net income indicator

$$D_i \to \max, \quad i = \overline{1, n_i}, \tag{3}$$

and the objective function is

$$D_0 = \max_{\{i\}} D_i = \max_{\{i\}} \left[V_i - \left(A_i + C_i^{agr} + C_i^{recl} + C_i^o \right) \right], \quad i = \overline{1, n_i}. \tag{4}$$

In the expression (2), the current costs C_i of obtaining products consist of agricultural C_i^{agr} and operational costs C_i^o. Operational costs include the costs for depreciation and repair A_i, reclamation costs C_i^{recl} include the costs for system maintenance and water for irrigation on drained lands.

Accordingly, at the stage of reconstruction, the optimal parameters of the PS and other elements of the PDS are substantiated by the following complex optimization model (Volk 2023). Accordingly, at the stage of reconstruction, the optimal design of the PDS pumping unit and its constituent elements is substantiated according to the following complex optimization model

$$\begin{cases} ZP_0 = \min\limits_{\{i\}} \sum\limits_{n=1}^{n_p} ZP_{ip} \cdot \alpha_p, \quad i = \overline{1, n_i}; \\ q_0 = \min\limits_{\{i\}} \sum\limits_{n=1}^{n_p} D_{ip} \left| q_s - \hat{q}_{ecol} \right| \cdot \alpha_p, \quad i = \overline{1, n_i}, \end{cases} \tag{5}$$

where ZP_0 – is the optimal value of the criterion by the i-th variant of PD population $\{i\}$, $i = \overline{1, n_i}$, UAH/ha.

The general economic criterion for optimization is *the given costs* Z, reduced to a comparative form ZP by the volume (cost) V of the received products in the variants of the technical solutions of the population $\{i\}$, $i = \overline{1, n_i}$ – types and designs of the polder systems, determined by the accepted methods and schemes of water regulation Volk 2023, Frolenkova 2023)

$$ZP_i = Z_i \cdot k_{Z_i}^V = \frac{C_i + E_n K_i}{V_i}, \quad i = \overline{1, n_i}, \tag{6}$$

where $k_{Z_i}^V$ – is the summation coefficient of the given costs Z_i by the volume (value) V_i of the obtained products by the variants of the technical solutions of the population $\{i\}$, $i = \overline{1, n_i}$, which is determined by the inverse ratio $1/V_i$; C_i – current costs for obtaining products by the variants of technical solutions; E_n – normative coefficient of economic efficiency of capital investments K_i by the corresponding variants of technical solutions.

Then the expression (5) becomes:

$$ZP_0 = \min_{\{i\}} \left\{ \frac{\left(A_i + C_i^{agr} + C_i^{o} + C_i^{recl}\right) + E_n K_i}{V_i} \right\}, \quad i = \overline{1, n_i}. \tag{7}$$

The substantiation of the optimal water regulation technology for the current PDS is carried out according to the appropriate optimization model, which is similar to model (5).

The work of the drainage on the PDS when using the drying mode leads to an increase in the flushing water regime in different vegetation periods in terms of heat and moisture supply. As a result of that, soil fertility decreases due to leaching of nutrients and disruption of the soil structure. Therefore, the deviation of the weighted average value of the drainage coefficient within the system and the design term of the object's operation q_s from its limit value $\hat{q}_{ecol}$, which corresponds to the ecological drainage efficiency, i.e. $q_s \rightarrow \hat{q}_{ecol}$ can be a criterion for the ecological optimality of the pumping module on the PDS (Koptyuk et al 2023).

The minimization of the drainage coefficient leads to an increase in the overall moisture supply within the DS, which is extremely relevant for drained peat soils under conditions of climate change (Shang 2014, Su et al 2019, Volk 2023).

The mentioned issues were solved on the example of the modernization of the "Birky" PDS on an area of 544 hectares, which is located in the Volodymyretsky district of the Rivne region (Fig. 2). In view of its design, the system can implement all the main technologies of water regulation on drained lands: drainage with mechanical pumping and regular drainage, preventive sluicing, subsoil irrigation and sprinkler irrigation. Soils on the site are medium-thick, well-decomposed, medium-ash peat on alluvial sandy loams with a filtration coefficient (k_f = 1.2 m/day). Cultivated crops were winter wheat (fractional share (f_k = 0.1); potatoes (f_k = 0.1); vegetables (f_k = 0.3); grass (f_k = 0.5).

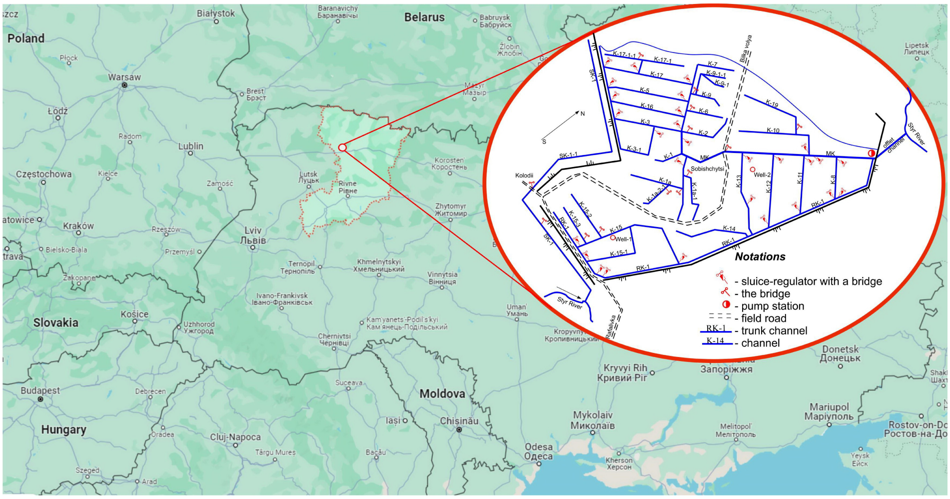

Fig. 2. Scheme of the location of the PDS "Birky"

Compared with the existing designs, the proposed design of the pumping unit with the slotted tubular dam opening (patent No.153154) and siphon (patent No. 155116). Depending on the water content of the year, this makes it possible to increase the efficiency of the PDS operation by reducing the load on the pumping equipment by redistributing the pumping flow to the corresponding gravity elements of the pumping unit.

The following complex of technological and technical measures for the modernization of the object is foreseen before the implementation: clarification of the calculation module of pumping; improvement of the existing design and parameters of the pumping unit, which consists of a pumping station and a slotted tubular dam opening (PS + Stdo), due to the additional installation of a siphon (PS + Stdo + S); clarifying the water regulation scheme on the system, as well as performing a comparative assessment of the ecological, economic and investment efficiency of project solutions, technologies for the development of PDS projects.

The sequence and structure of performing optimization calculations includes:

1. Justification of the optimal parameters of the pumping module according to model (1) for changing its parameters in the range of 0.8–1.2 l/s·ha, with its design value of 1.15 l/s·ha;
2. Justification of the design of the pumping unit according to model (5) for the following options: PS + Stdo, PS + S, PS+ Stdo + S (Fig. 3).
3. Justification of the technology of water regulation of drained lands for PDS according to options, which include the operation of the system in the mode of drainage (DM), preventive sluicing (PS), moistening sluicing (MS); sprinkler irrigation against the background of preventive sluicing (PrS) and their possible combinations for current and forecast weather and climate conditions.

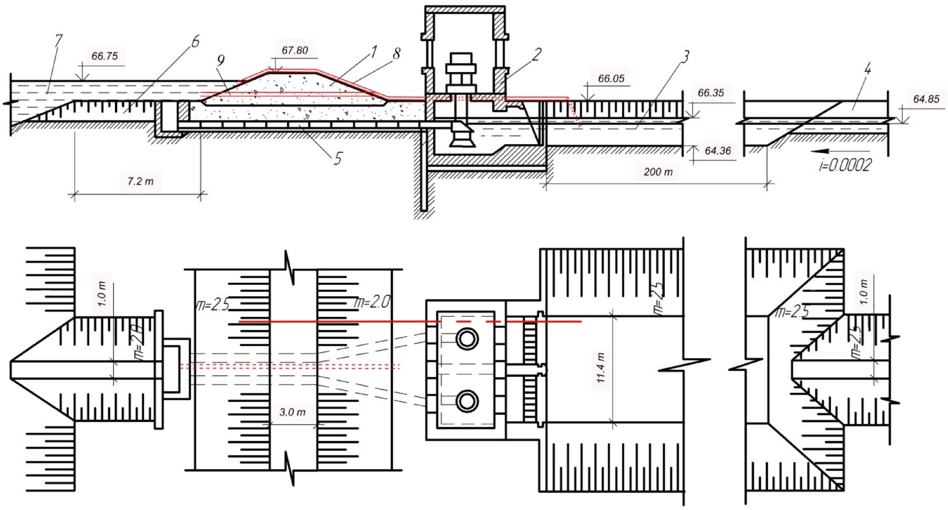

Fig. 3. Scheme of the pumping unit: 1 – dam; 2 – premises of the pumping station; 3 – regulating pool; 4 – main canal; 5 – pressure pipeline; 6 – derivation canal; 7 – intake chamber; 8 – siphon intake; 9 – the slotted tubular dam opening

A hierarchically connected complex of predictive and simulation models was used to implement the considered optimization models. The practical application of these models is regulated by relevant industry standards of the State Water Agency of Ukraine for local climatic conditions or meteorological regimes, water regime and water regulation technologies of drained lands and their productivity of drained lands (Handbook…2023).

3. Research Results and Their Discussion

The generalized results regarding the substantiation of the technological and structural parameters of the PDS according to the optimization approach are presented in Tables 1–6.

A fragment of the results of optimization calculations to determine the optimal pumping module for the object under study is presented in Table 1.

By the results of prediction and optimization calculations, it was determined that the optimal pumping module for the studied object is = 0.95 l/s·ha when having the net income indicator D_i = 29057 UAH /ha.

A fragment of the results of relevant of prediction and optimization calculations for determining the optimal design of the PDS pumping unit for the optimal pumping module for the object under study is presented in Table 2.

In turn, for the optimal pumping module due to reconstruction, the optimal design of the PDS pumping unit is determined by the optimization model (5) when

Table 1. Summarized results of optimization calculations to determine the optimal pumping module of PDS

Crop	f_k	q_{PDS}, l/s·ha	Y_n, c/ha	Y_{ah}, c/ha	D_i, UAH/ha
q_{PDS} = **0.9** l/s·ha					
Winter wheat	0.2	0.9	39.0	24.5	10641.4
Potato	0.2	0.9	390.0	245.7	35894.2
Vegetables	0.1	0.9	292.5	184.2	20025.6
Grass	0.5	0.9	390.0	245.7	35936.1
q_{PDS} = **0.95** l/s·ha					
Winter wheat	0.2	0.95	39.44	24.8	11513.2
Potato	0.2	0.95	394.4	248.4	38112.3
Vegetables	0.1	0.95	295.8	186.3	21273.6
Grass	0.5	0.95	394.4	248.4	38154.9
q_{PDS} = **1.0** l/s·ha					
Winter wheat	0.2	1.0	40.6	25.5	11287.4
Potato	0.2	1.0	406.5	256.0	37365.3
Vegetables	0.1	1.0	304.9	192.0	20855.7
Grass	0.5	1.0	406.5	256.0	37406.5
At the system level as a whole	1.0	0.9	–	–	27362.6
		0.95	–	–	**29057.8**
		1.0	–	–	28487.6

Note: – PDS pumping module, l/s·ha (liter per second from 1 hectare); Y_n – project yield, c/ha (centner per hectare); Y_{ah} – actual yield, c/ha.

$ZP_0 = 0.4037$. The optimal design includes a PS, the slotted tubular dam opening and a siphon (Fig. 2) with the following distribution of estimated costs as a whole for the system and for the elements of the pumping unit, respectively: $Q_C^0 = 0.51$ m^3/c; $Q_{PS}^0 = 0.38$ m^3/c; $Q_{Stdo}^0 = 0.01$ m^3/c; $Q_{siphon}^0 = 0.12$ m^3/c.

Thus, due to the redistribution of water flows by the improved design of the pumping unit with additional elements, a reduction in costs and the volume of water pumped by the PS and electricity consumption is achieved by 35%.

The determined economically optimal technological and design solutions for the object under study are environmentally acceptable under the given conditions, since the weighted average value of the drainage coefficient within the system and the design term of its operation $q_s = 0.38$ l/s·ha corresponds to the ecological drainage efficiency, i.e. $q_s \leq \hat{q}_{ecol}$.

An example of the economic feasibility of investment projects regarding the optimal design and parameters of the pumping unit for a PDS "Birky" is presented in Table 3.

The main economic indicators for calculation in specific form regarding the optimal technology of water regulation of drained lands at DPS "Birky" in modern and forecasted climatic conditions, according to (Handbook... 2023), according to the relevant options are given in Table 4.

Thus, the given results show that at the preliminary stage of the evaluation of design solution options for the optimal pumping module, the optimal option for the

Table 2. Summarized results of optimization calculations to determine the optimal design of the PDS pumping unit

Design of PDS	q_{PDS}, l/s·ha	Y_n, c/ha	Y_{ah}, c/ha	$V_{Y\phi}$, UAH/ha	C_i^{agr}, UAH/ha	C_i^{recl}, UAH/ha	C_{pum}, UAH/ha	A_i, UAH/ha	Z_i, UAH/ha	XP_i
Winter cereals										
PS+Stdo	0.80	37.80	23.8	3808	1730.1	1534.6	457.9	203.5	3604.1	0.4609
PS+ Stdo +S	0.80	37.80	23.8	3808	1730.1	1390.9	314.0	203.6	3460.5	0.4587
PS+S	0.80	37.80	23.8	3808	1730.1	1416.9	340.2	203.5	3486.3	0.4591
Potato										
PS+ Stdo	0.80	378.0	238.1	9520	4469.5	1534.6	457.9	203.5	6343.5	0.4086
PS+ Stdo +S	0.80	378.0	238.1	9520	4469.5	1390.9	314.0	203.6	6199.9	0.4085
PS+S	0.80	378.0	238.1	9520	4469.5	1416.9	340.2	203.5	6225.7	0.4085
Vegetables										
PS+ Stdo	0.90	292.5	184.2	7617	3098.0	1591.9	515.2	203.5	5029.2	0.3913
PS+ Stdo +S	0.90	292.5	184.2	7617	3098.0	1430.2	353.2	203.6	4867.6	0.3911
PS+S	0.90	292.5	184.2	7617	3098.0	1459.4	382.7	203.5	4896.7	0.3911
Grass										
PS+ Stdo	0.95	394.4	248.4	8377	3909.9	1620.5	543.8	203.5	5869.7	0.3824
PS+ Stdo +S	0.95	394.4	248.4	8377	3909.9	1449.8	372.9	203.6	5699.1	0.3823
PS+S	0.95	394.4	248.4	8377	3909.9	1480.7	403.9	203.5	5729.9	0.3824
At the system level as a whole										
PS+ Stdo										0.4049
PS+ Stdo +S										**0.4037**
PS+S										0.4041

Note: PS+ Stdo – design and parameters of the PDS when PDS during the operation of the pumping station with the slotted tubular dam opening; PS+ Stdo +S – design and parameters of PDS during the operation of the pumping station with the slotted tubular dam opening and a siphon; PS+S – design and parameters of PDS during the operation of the pumping station with a siphon.

Table 3. The main economic indicators regarding the reconstruction of the design parameters of PDS, UAH/ha

No	Indicator	Design and parameters of the pumping unit of PDS		
		PS+Stdo	**PS+Stdo+S**	**PS+S**
1	Capital investment in reconstruction	723.872	**904.84**	814.356
2	Depreciation of fixed assets	180.968	**226.21**	203.589
3	Net income	182.84	**312.35**	254.48
4	Given costs	0.541	**0.458**	0.476

construction of the PDS pumping unit will be the PS+Stdo+S option, and from the various considered technologies of water regulation of drained lands for modern climatic conditions, preventive sluicing is the best option. And for forecast conditions, there can be humidification sluicing and sprinkler irrigation.

An example of the economic feasibility of the investment project regarding the optimal design and parameters of the PDS pumping unit (PS+Stdo, PS+Stdo+S, PS+S) was implemented for the conditions of the real object under study.

The generalized results on the assessment of the investment efficiency of the considered design solution for the object under study are shown in Table 5.

Table 4. Main economic indicators of PDS, UAH/ha

No	Indicator	Water regulation technology							
		D	**PS**	**MS**	**SD**	**D**	**PS**	**MS**	**SD**
		Current conditions				**Predictive conditions**			
1	Capital investment in reconstruction	84260	**88360**	126760	164160	84260	88360	**126760**	**164160**
2	Current costs:	39790	**42907**	49758	53257	55837	59994	**68511**	**78351**
	– agricultural	36138	**38774**	40187	40552	52185	55861	**58940**	**65645**
	– operational	1124	**1482**	3233	4498	1124	1482	**3233**	**4498**
	– depreciation of fixed assets	2528	**2651**	6338	8208	2528	2651	**6338**	**8208**
3	Gross production	47587	**51273**	54480	58553	69318	75543	**84795**	**95916**
4	Net income	10325	**11017**	10666	12824	16009	18200	**21885**	**24799**
5	Given costs	1.667	**1.542**	1.606	1.59	1.79	1.613	**1.48**	**1.369**

Note: drainage (D); preventive sluicing (PS); moisturizing sluicing (MS); sprinkling on the background of drainage (SD).

Table 5. The main indicators of the economic efficiency of investments in the reconstruction of the PDS pumping unit

No	Indicator	Design and parameters of PDS		
		PS+Stdo	**PS+Stdo+S**	**PS+S**
1.	NPV, UAH/ha	2209	**3436**	2878
2.	IRR,%	4.05	**4.80**	4.53
3.	DPP, years	3	**2**	4

Note: usually, indicators used to make investment decisions are the net profit value (NPV), profitability index (PI), discounted payback period (DPP) and internal rate of return (IRR) (Handbook... 2023).

The obtained results on the investment evaluation of design solution variants confirm both the economic and sufficiently high commercial efficiency of the PS+Stdo+S variant. The highest values of the profitability index were UAH 3436/ha for the PS+Stdo+S variant. The payback period for capital investments for this variant is 2 years, which is quite promising and can ensure a quick repayment of investments.

The results of the final calculations regarding the determination of investments in the reconstruction of the "Birky" PDS when substantiating various technologies of water regulation of drained lands in the current and forecast conditions of the operation of the object under consideration are presented in Table 6.

Table 6. The main indicators of the efficiency of investments in water regulation technologies of drained lands

No	Indicator	Water regulation technology							
		D	**PS**	**MS**	**SD**	**D**	**PS**	**MS**	**SD**
		Current conditions				**Predictive conditions**			
1.	NPV, UAH/ha	**19342**	**21810**	10306	5376	65158	79715	**100734**	101898
2.	IRR,%	**1.23**	**1.25**	1.08	1.03	1.77	1.90	**1.79**	1.62
3.	DPP, years	**11**	**11**	13	15	7	6	**7**	7

The calculations made regarding the investment evaluation of the optimal PD variants show that in current conditions drainage and preventive sluicing with a discounted payback period of 11 years can be such a variant of water regulation technology. Accordingly, in predictive conditions, preventive sluicing with a discounted payback period of 7 years can be quite promising and can ensure a quick investment repayment in the facility reconstruction.

4. Conclusions

The substantiation of the technological and design parameters of the PDS in accordance with the optimization approach by using an appropriate set of optimization and predictive simulation enables to carry out the following:

1. To substantiate the optimal pumping module at the stage of operation for the operating PDS.
2. To improve the design of the pumping unit and the parameters of its components during the reconstruction of the PDS, which makes it possible to reduce the load on the pumping equipment, the duration of its operation, and, accordingly, the cost of electricity by 20–40%, depending on the water level of the year, due to the diversion of the corresponding part of the surface runoff with additional gravity elements in the form of a slotted tubular dam opening and siphon.
3. To justify the optimal water regulation technology for the current PDS in current and forecast weather and climate conditions, which will ensure the maintenance of the necessary water-air regime of drained soils in different phases of vegetation of cultivated crops.

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