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RESEARCH ARTICLE

Reclamation of Irrigated Lands and Improvement of the Groundwater Regime Under Vertical Drainage Operation

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Abstract: The aim of the study was to identify patterns of seasonal groundwater-level fluctuations and assess the effectiveness of vertical drainage in regulating the reclamation regime of saline lands in Kazakhstan. The methods included monitoring-well observations, calculation of seasonal amplitudes, Student's t-test, the Mann-Whitney U test, and Pearson correlation analysis. Before the growing season, groundwater occurred at a depth of 1.5-1.7 m, corresponding to the critical threshold for secondary salinisation. By days 5-6 after the inflow of irrigation and meltwater, groundwater became shallower rapidly, with the rate of shallowing increasing from 0.20-0.30 m/day during the initial stage to 0.80-0.90 m/day. From 2021 to 2024, a stable annual cycle was recorded: a spring shallowing to 1.4-1.6 m depth, a summer deepening to 2.5-3.3 m depth. Drainage-system operation remained stable throughout the leaching period. The average discharge was 38 L/s, while the volume of pumped water ranged from 260.35 to 325.45 thousand m³. The efficiency coefficient remained at 0.96-0.97 despite a reduction in operating duration from 10 to 8 days and a decline in energy consumption toward the end of the cycle. Seasonal analysis showed that operational coefficients of 0.25-0.30 maintained stable drainage during transitional and summer periods, whereas a coefficient of 0.50 was required during periods of increased hydrological load. The findings confirm that vertical drainage effectively regulates groundwater levels, supports a stable reclamation regime, and reduces the risk of secondary soil salinisation. The results can be used to set vertical-drainage operating coefficients at 0.25–0.30 during stable summer conditions and increase them to 0.50 during spring and early-autumn peak recharge to maintain groundwater below the secondary-salinisation threshold while reducing unnecessary pumping and energy consumption.

Keywords: Leaching Period, Pumping Volume, Water Level Rise, Efficiency Coefficient, Discharge

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Introduction

The relevance of this study is determined by the need to maintain rational water use on irrigated lands under conditions of limited water resources. In modern agriculture, vertical drainage plays a key role in regulating groundwater levels, reducing soil salinity, and preventing degradation processes. Increased water consumption in the agricultural sector, combined with changing natural conditions, places greater pressure on existing reclamation systems. In this context, assessing the operational characteristics of vertical drainage and their efficiency becomes particularly important, as it is directly linked to the productivity of agro-landscapes and the environmental sustainability of regions.

The problem addressed in this study is associated with the lack of systematised data on the interaction between the operational regimes of drainage wells and groundwater level dynamics under conditions of seasonal fluctuations and the leaching of saline lands. Insufficient information on the actual performance of equipment, its energy efficiency, and its impact on water-salt balance processes complicates decision-making in the field of land reclamation. Moreover, in some cases, existing approaches are limited to local observations without comprehensive analysis, which reduces the capacity for forecasting and adapting drainage systems to changing conditions.

In a study devoted to improving water use in reclamation systems, [1] showed that the introduction of innovative technologies in irrigation canals reduced seepage losses and increased drainage efficiency. It was demonstrated that reducing seepage is directly important for preventing secondary salinisation. The issue of restoring abandoned lands was addressed in studies where [2] found that the application of reclamation measures altered the ecological and hydrological condition of territories, and that the involvement of such lands was accompanied by changes in agro-landscape parameters.

From a practical perspective, the issue of waterlogging of agricultural lands was raised by [3], who demonstrated that excessive waterlogging reduced soil productivity and required engineering solutions. It was confirmed that groundwater level control plays a key role in ensuring sustainable agriculture. The literature also addressed issues of salt balance management, with [4] noting that effective use of saline soils is possible when leaching is combined with drainage systems. It was established that drainage is a fundamental condition for long-term reclamation sustainability.

Using large-scale projects as examples, experience from Egypt was analysed by [5], who found that the organisation of groundwater control was a central element in the operation of irrigated areas. It was noted that rational regulation of the water balance ensures the productivity of large reclamation systems. Within studies of coastal territories, processes of salt redistribution were highlighted, where [6] showed that drainage measures in low-permeability zones altered the structure of underground horizons, and that transformation of the water-salt regime has a long-term impact on agroecosystems.

The context of land development was reflected in a study by [7], which showed that drainage measures combined with irrigation contributed to the expansion of agricultural areas, and that groundwater control was a key condition for successful reclamation. Water resource management was examined by N.F.A. El Azim et al. [8], who found that regulating water supply to elevated areas requires optimisation of operational regimes, and emphasised that coordinated operation of pumping stations reduces system load and ensures stable water supply.

Hydrological issues were analysed by [9], who showed that insufficient performance of drainage structures caused stagnation and soil waterlogging, and demonstrated that the use of geophysical and hydrological methods allows identification of zones of potential water saturation. A historical aspect was addressed by [10], who established that drainage works already played a significant role in agricultural development in the 3rd century AD, confirming that water balance management was the basis of agricultural productivity in antiquity.

A comparative approach was used by [11], who showed that optimisation of groundwater depth and drainage coefficients helps to reduce nutrient losses, indicating that correct parameter selection ensures the sustainability of reclamation systems. A reclamation perspective was outlined by [12], who found that integrated measures for the development of solonetzic soils increase their productivity, and demonstrated that a systemic approach creates long-term prospects for the effective use of saline territories. Issues related to the long-term energy efficiency of vertical drainage, the integration of climatic factors into its operational models, and its impact on biodiversity in reclaimed ecosystems remain insufficiently studied.

Previous studies have established the importance of drainage for controlling shallow groundwater and reducing salinisation risk; however, limited evidence is available on how the actual operating regime of vertical drainage corresponds to seasonal groundwater fluctuations under the specific hydrogeological conditions of the Turkestan Region. In particular, earlier research has rarely combined multi-year groundwater monitoring with ten-day and monthly operational records, including pumping duration, discharge, pumped-water volume, energy consumption, and operational coefficients. The scientific novelty of the present study therefore lies in the integrated analysis of groundwater-level dynamics during 2021–2024 and the operational characteristics of vertical drainage, which makes it possible to identify the seasonal correspondence between drainage-system load and groundwater drawdown. This regional evidence provides a basis for determining when drainage intensity should be increased, maintained, or reduced under irrigated saline-land conditions.

The aim of the study was to assess the operational characteristics of vertical drainage and their influence on groundwater level dynamics under the conditions of the Turkestan Region. The objectives included analysing the operating regimes of vertical drainage wells, comparing operational parameters with groundwater level dynamics, and evaluating the system efficiency coefficient.

Materials and Methods

The study used data for 2021-2024 collected at reclamation sites in Kazakhstan, Turkestan Region [13]. The observation objects included groundwater levels, operational characteristics of vertical drainage wells, indicators of operating regimes during the leaching period, and the annual distribution of load by ten-day periods. This approach made it possible to cover the full operational cycle of drainage systems, including spring, summer, autumn, and winter phases, and to establish relationships between operational parameters and the state of the aquifer. To study groundwater level dynamics, observation data from a network of monitoring wells in the Turkestan Region for 2021–2024 were used [14]. Depth measurements were carried out at ten-day intervals, ensuring detailed recording of seasonal changes. Indicators were recorded with an accuracy of 0.1 m using standard water-level measuring instruments. The collected values were combined into time series, on the basis of which seasonal cycle patterns were identified. The analysis methodology included calculation of minimum and maximum levels, seasonal amplitudes, and identification of phases of spring shallowing, summer deepening, and autumn-winter stabilisation. Statistical smoothing methods were applied to identify stable trends and eliminate random fluctuations.

Cotton (*Gossypium hirsutum L.*) was the principal crop considered in the agronomic interpretation of groundwater conditions at the studied irrigated sites. Under irrigated field conditions, the effective rooting depth of cotton is approximately 0.9 m, although root development may vary depending on soil texture, compaction, moisture, and salinity. Therefore, groundwater occurring at a depth of 1.5–1.7 m was only 0.6–0.8 m below the effective root zone. Under saline-soil conditions, this distance may permit capillary transport of mineralised groundwater towards the root zone, increasing the risks of poor aeration, excessive moisture, and salt accumulation. Accordingly, the groundwater depth of approximately 1.5 m was treated as a practical warning threshold for cotton cultivation rather than as a universal threshold applicable to all crops.

Analysis of the operational characteristics of vertical drainage was carried out using data from operational logs of pumping stations [15]. The main indicators considered were operating duration in days, average discharge in litres per second, total volume of pumped water in thousands of cubic metres, electricity consumption in kilowatt-hours, and the efficiency coefficient. Data were recorded in ten-day periods of the March leaching period, which allowed differences between initial, intermediate, and final stages of leaching to be taken into account. Discharge measurements were carried out using flow meters with subsequent conversion to average daily values; pumped water volumes were determined as integral discharge values over each ten-day period. Energy parameters were calculated from electricity meter readings and expressed as specific consumption per 1,000 m³ of water. The efficiency coefficient was calculated as the ratio of actual operational data to design values using Equation (1):

$$K_э = \frac{Q_f}{Q_p}, \tag{1}$$

Where: $K_э$ is the efficiency coefficient, Q_f is the actual value, Q_p is the planned pumping volume specified in the drainage-system design documentation. The baseline value was determined from the rated design discharge of the wells and their scheduled operating duration for each ten-day period. Thus, the coefficient reflects the extent to which actual drainage performance corresponded to the planned design capacity.

The annual operating regime of drainage wells was analysed using data for 2022 collected in the Turkestan Region [16]. The year 2022 was selected because it was characterised by typical hydrological conditions and reflected an average level of drainage well operation without extreme deviations in water regime. The main parameter used was the operational coefficient, calculated as the ratio of actual operating time of wells to the calendar duration of the ten-day period. The obtained coefficients were grouped by months and ten-day periods, which made it possible to identify seasonal patterns and record periods of maximum activity in spring and early autumn, stable loads in summer, and minimal operation in winter. Processing included calculation of mean values, median, standard deviation, and analysis of variance to determine the significance of the temporal factor (year, month, ten-day period) for changes in operational characteristics.

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To compare operational parameters of drainage wells with groundwater level dynamics, materials collected for 2021-2024 in the Turkestan Region were used [17]. The analysis included three main indicators: efficiency coefficient, well operating duration in hours, and groundwater depth in metres. Additionally, cumulative annual indicators were calculated: the average annual operational coefficient and total system operating time per calendar year. Descriptive and comparative statistical methods were applied. The significance of differences between seasonal phases was tested using Student's t-test; distribution analysis was performed using the Mann-Whitney U test [18]; and the relationship between operational parameters and groundwater depth was determined using Pearson correlation [19]. Analysis of variance made it possible to identify the significance of the temporal factor and the stability of operational patterns. Energy indicators were calculated from actual energy consumption by pumping equipment and converted into specific values, expressed as kWh per 1,000 m^3 of pumped water.

Results

Seasonal Changes in the Depth of Groundwater Horizons

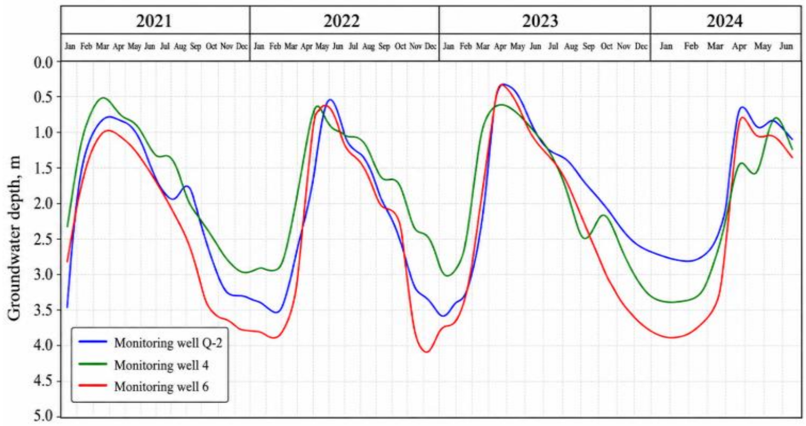
Before the start of the growing season, the groundwater level in Southern Kazakhstan was recorded at a depth of 1.5-1.7 m, which corresponded to the hazardous threshold of secondary salinisation set at 1.5 m as the limiting value at which capillary rise reaches the plant root zone. When irrigation and meltwater entered the system, rapid saturation of the aeration zone occurred, and a capillary fringe formed and connected with the groundwater horizon. By days 5-6, the rate of groundwater-level rise reached its measured maximum of 0.80-0.90 m/day, consistent with saturation of the aeration zone and connection of the capillary fringe with the groundwater horizon. The rate of change in depth was uneven: during the first two days it was 0.20- 0.30 m/day, by the fourth day it reached 0.80–0.90 m/day, after which it decreased to 0.10-0.15 m/day. This process reflected a short-term phase of sharp rise followed by stabilisation.

Regional climatic conditions were considered when interpreting groundwater-level fluctuations. In 2021, the mean annual air temperature in the Turkestan Region was 2.34°C above the climatic norm. In 2023, heatwaves in southern Kazakhstan lasted more than 30 days and locally exceeded 60 days, increasing evaporation and crop water demand. In March 2024, precipitation at the Ashchysay meteorological station reached 175.3 mm, equivalent to 238.2% of the long-term norm, indicating unusually high spring moisture input. These climatic conditions help explain the rapid groundwater recharge observed in spring and the subsequent groundwater-level decline during the hot and dry summer period. Because the climatic observations were regional or station-specific rather than collected directly at each monitoring well, they were used for contextual interpretation and not as variables in the statistical analysis.

In 2021, seasonal dynamics were characterised by a recurring cycle. In spring, the depth decreased to 1.4-1.5 m, then increased to 2.5-2.7 m in June–July. By August- September, groundwater depth reached 3.0 m and remained within this range through the ten-day observation periods of both months. Thus, the annual cycle included three successive stages: spring rise, summer decline, and autumn-winter equilibrium. According to materials collected in 2021, the seasonal course of groundwater levels had a similar character [20]. Groundwater was shallowest in spring, at about 1.6 m, and deepest in summer, at 3.2 m, and by winter the depth stabilised at 2.6-2.8 m. It was emphasised that the spring period was the most critical, as it coincided with the active development phase of crops and required strict regulation.

In 2022, the same seasonal pattern was maintained. In April, groundwater became shallower, to 1.5 m, then by July deepened to 2.8 m, and in August–September it reached 3.1-3.2 m. In autumn, stabilisation within 2.7 m was recorded. This year was characterised by increased irrigation load, which caused a sharper spring rise; however, the overall dynamics remained manageable. A study for 2022 reported that the seasonal fluctuation amplitude was about 1.6 m [21]. The spring maximum occurred in March-April, the summer decline was recorded by the end of August, and winter conditions were maintained at 2.6-2.8 m. It was noted that, despite precipitation shortfalls, the cycle remained consistent, and vertical drainage maintained the level within acceptable parameters. In 2023, the seasonal dynamics curve remained stable. In spring, the level rose to 1.4-1.5 m; in summer, it declined to 3.0-3.1 m; and in winter, values were recorded at around 2.7 m. The spring peak was more pronounced, which was associated with increased water supply volumes, but the overall cycle shape remained stable. According to published data for 2023, seasonal changes varied within 1.5-2.0 m [22]. Shallowing occurred in March-April; summer deepening reached 3.0-3.2 m, and stabilisation was noted in autumn and winter. It was concluded that regular drainage operations made it possible to keep dynamics within normative limits and prevented the development of salinisation processes.

In 2024, the seasonal cycle confirmed the predictability of groundwater level behaviour. In spring, depth was about 1.6 m; by August-September it increased to 3.2-3.3 m; and in December it stabilised at 2.7 m. Regardless of changes in climatic conditions, the repeatability of the curve remained unchanged. Based on the analysis of materials from recent years, it was concluded that the seasonal groundwater-level cycle was stable and reproducible [23-25]. A spring rise to 1.5-1.7 m, a summer decline to 3.0-3.3 m, and winter stabilisation at 2.6-2.8 m were characteristic. The stability of this rhythm was regarded as a regular pattern for conditions of vertical drainage operation, which ensures the maintenance of an agronomically acceptable soil regime (Figure 1).



Source: compiled by the authors based on the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan [13, 14]

Fig. 1: Groundwater level dynamics (2021-2024)

Thus, data for 2021-2024 showed that groundwater-level dynamics in the Turkestan Region followed a recurring annual cycle, in which the spring maximum posed a potential risk of salinisation, the summer minimum provided optimal conditions for agricultural production, and winter stabilisation assured the system's equilibrium. Such predictability confirmed the need for continuous regulation through vertical drainage and indicated the stability of the reclamation effect under intensive irrigation. The functioning of vertical drainage during the leaching period was characterised by a set of indicators including well operating duration, average discharge, total volume of pumped water, electricity costs, and the efficiency coefficient. Systematisation of these data made it possible to identify operating patterns and assess the stability of operational characteristics under intensive leaching of saline lands. The combination of hydraulic and energy parameters reflected the degree of rationality of the process and demonstrated the potential for regulating the water regime under high load.

Operational Parameters of Drainage Systems During Leaching

In the first ten-day period of March, the operating duration was 10 days, corresponding to full loading of the drainage system. The average discharge was maintained at 38 L/s, ensuring uniform pumping and eliminating sharp fluctuations in inflow. During this period, 325.45 thousand m³ of water was removed from the aquifer. Energy consumption reached 4,467.2 kWh, and the efficiency coefficient was 0.97. This value indicated an almost complete correspondence between actual and calculated values and characterised the initial leaching stage as the most effective. [26] noted that it is precisely the first ten-day period that provides the maximum return from drainage wells due to the high-pressure gradient and intensive inflow of seepage water. In the second ten-day period of March, well operation also lasted 10 days. The average discharge remained stable at 38 L/s, confirming the reliability of the technical regime. The total volume of pumped water was 325.45 thousand m³, the same as in the first ten-day period. However, energy consumption decreased to 4,407.2 kWh, and the efficiency coefficient declined slightly to 0.96. This minor decrease was explained by stabilisation of seepage inflow as the system shifted from maximum load to a more even distribution of drainage. The study emphasised that such changes were not negative but indicated a normal process of system adaptation to reduced head [27]. Operational indicators remained within optimal values and met reclamation requirements.

In the third ten-day period of March, the operating duration was reduced to 8 days with an unchanged average discharge of 38 L/s. Over this time, the volume of pumped water amounted to 260.35 thousand m³, while energy consumption decreased sharply to 416.6 kWh. The efficiency coefficient remained at 0.96, confirming stable system performance even with shorter operating time. The reduction in duration and pumping volume reflected the natural completion of the active leaching stage, when the groundwater level evened out, and seepage inflow declined. Published data indicated that the final stage of the cycle is always accompanied by reduced load and energy consumption while maintaining overall effectiveness of the process [28]. Comparison of the three ten-day periods showed that operational parameters were highly stable. Duration varied from 8 to 10 days, but discharge remained constant at 38 L/s, confirming stable system operation regardless of external conditions. The total volume of pumped water ranged from 260.35 thousand m³ in the last ten-day period to 325.45 thousand m³ in the first two. Energy consumption varied from 4,467.2 to 416.6 kWh, reflecting a gradual reduction in load. The efficiency coefficient remained within 0.96- 0.97, demonstrating minimal fluctuations and high process reliability. The study emphasised that discharge constancy and stability of the efficiency coefficient were the main criteria for effective vertical drainage performance [29, 30].

Analysis of operational characteristics confirmed that the reduction in energy consumption from the first to the last ten-day period was viewed as a positive factor associated with rational load distribution and the completion of active leaching. According to the study, an efficiency coefficient within 0.95-0.98 reflects an optimal operating regime of drainage systems, and the indicators fully fell within this range [29]. Pumping volumes fully corresponded to reclamation objectives, ensuring a reduction in groundwater level and preventing secondary salinisation processes (Table 1).

Table 1: Operating regime of the drainage system during leaching of saline lands

Work period, March-decade	Duration of operation of vertical drainage wells, days	Average flow rate, l/s	The volume of pumped-out water, thousand m^3	Electricity consumption, kW/h	Efficiency coefficient
1	10	38	325.45	4,467.2	0.97
2	10	38	325.45	4,407.2	0.96
3	8	38	260.35	416.6	0.96

Source: compiled by the authors based on [15]

Thus, operation during the leaching of saline lands demonstrated stability of the main parameters, high productivity, and rational energy use. Regardless of the reduced operating duration in the final ten-day period, operational indicators remained within normative values. The efficiency coefficient remained within 0.96-0.97 of the planned design pumping volume throughout the leaching period, indicating that actual drainage performance closely approximated the system's rated design capacity.

The sharp reduction in electricity consumption during the third ten-day period resulted from the transition from continuous to intermittent well operation as the active leaching phase ended and groundwater inflow decreased. Although the period covered 8 days, the pumping equipment operated for substantially fewer hours, with fewer wells activated simultaneously, while the reported average discharge of 38 L/s referred only to periods of actual pumping. Consequently, the decline in energy consumption was considerably greater than the reduction in calendar operating duration.

Monthly Distribution of Drainage System Load Throughout the Year

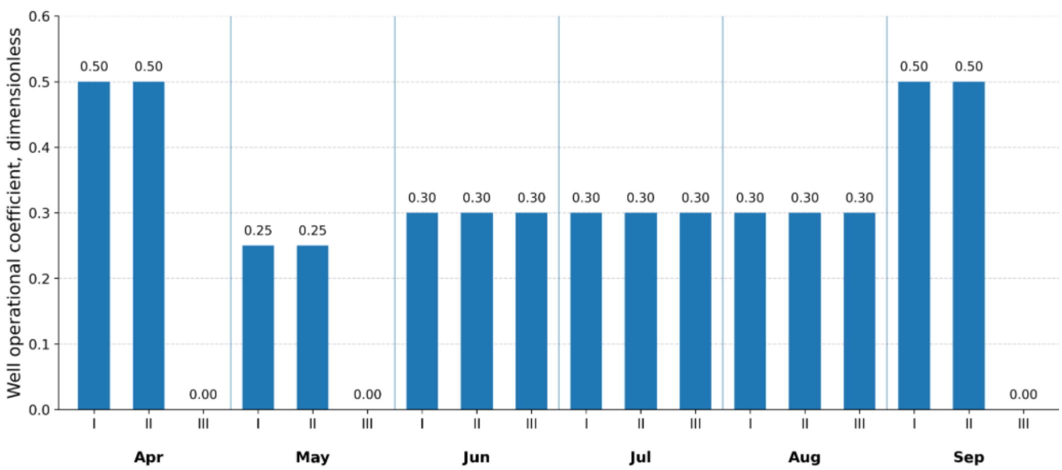
Vertical drainage operation throughout 2022 followed a stable seasonal rhythm, expressed in changes in the operational coefficient of wells by months and ten-day periods. The growing season was characterised by high activity, whereas the autumn-winter season was accompanied by a reduction in load to minimal values. Research materials noted that the identified dynamics were linked to general patterns of the soil water regime as well as seasonal fluctuations in groundwater level that determine the intensity of seepage processes [31]. The spring stage began with a sharp increase in operational indicators. In April, coefficient values reached 0.50 in the first and second ten-day periods, while in the third ten-day period they fell to 0.00. This load distribution structure was interpreted as reflecting maximum involvement of the drainage system at the beginning of the season and its stabilisation by the end of the month. [32] emphasised that April is considered a critical period requiring the most intensive drainage, as it coincides with the start of active crop vegetation and the period of high soil water saturation.

May was characterised by more moderate operational coefficient values. In the first and second ten-day periods, values were maintained at 0.25, while in the third ten-day period they declined to 0.00. This distribution reflected a gradual reduction in system load as seepage inflow stabilised and the risk of waterlogging decreased. Published materials indicated that the May operating regime is transitional: it makes it possible to preserve the reclamation effect while reducing energy consumption and preparing for the summer period of stable operation [33]. The summer months June, July, and August demonstrated parameter stability. Across all three ten-day periods, the operational coefficient remained at 0.30, indicating uniform system operation. This regime maintained a balance between irrigation input and timely drainage, preventing excessive rises in groundwater level. Researchers noted that the stability of summer indicators determines drainage-system reliability and creates conditions for uninterrupted crop growth during the period of maximum water demand [34, 35].

September again showed increased drainage activity. In the first and second ten-day periods, operational coefficients reached 0.50, while in the third ten-day period they fell to 0.00. Thus, the system operated in a short-term reinforcement regime, consolidating leaching results and preventing secondary soil salinisation. Research materials emphasised that the September cycle is crucial for maintaining the reclamation effect at the final stage of vegetation and ensuring a smooth transition to the autumn-winter period of minimal activity. Autumn months were accompanied by a sharp reduction in operational load. As early as October, operational coefficients decreased to values close to zero, corresponding to the actual cessation of active system operation. This trend continued in November and December, when indicators also remained at 0.00. Previous studies have noted that in autumn the main factor becomes not the intensity of pumping but the regularity of episodic switch-ons required to maintain hydraulic equilibrium and prevent excessive moisture accumulation due to atmospheric precipitation [28].

The winter period (December-February) was characterised by minimal operational activity. Operational coefficients remained close to 0.00, reflecting almost complete absence of need for intensive drainage operation. Published data indicate that this regime is typical for low-temperature periods, when seepage inflow decreases to minimal values. At the same time, the system remained technically ready for spring activation and could be used if local drainage became necessary [36-38]. Comparative analysis showed a clear contrast between seasons. In spring and early autumn, the system operated at maximum activity, with operational coefficients reaching 0.50. In summer, operation stabilised at 0.30, ensuring uniformity and reliability of drainage. May showed transitional conditions with coefficients of 0.25, reflecting a gradual reduction in load after the spring maximum. Autumn–winter months demonstrated actual cessation of active operation, with coefficients dropping to 0.00 and the system functioning only in a maintenance mode (Figure 2).

Thus, the operating regime during the growing season and the autumn-winter period showed pronounced cyclicality. Spring and early autumn were accompanied by peak coefficient values up to 0.50; summer was characterised by stable indicators at 0.30; May reflected transitional conditions with coefficients of 0.25; and winter demonstrated a reduction in load almost to zero. This dynamic confirmed the effectiveness of vertical drainage as an element of the reclamation system, ensuring a balance between drainage and energy consumption and preventing the development of adverse soil processes.



Source: compiled by the authors based on [16]

Fig. 2: Annual operating regime of vertical drainage by ten-day periods

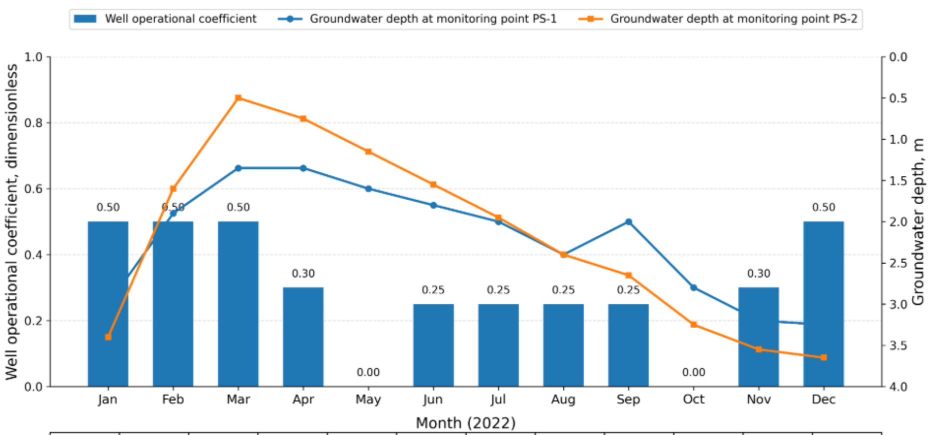
Integrated Indicators of Operation and Drainage Drawdown Depth

Seasonal fluctuations were pronounced: peaks in operational activity were observed in spring and autumn, the summer months were characterised by stabilisation of parameters, and the winter period was accompanied by reduced load and a shift to a maintenance mode. Research materials emphasised that such a distribution reflects regularities of the soil water regime and ensures the effectiveness of drainage systems during leaching and the growing season [39]. In the winter spring period, maximum operational values were recorded. In January-March, the wells' efficiency coefficients were 0.50, while operating time reached 372-336 hours per month. The groundwater level was maintained at a depth of 1.6-1.8 m, corresponding to the phase of meltwater accumulation and the need for its removal. High operational performance ensured regulation of the water balance and prevented waterlogging of the root zone. Published sources indicate that the first phase of the year sets the key conditions for stable functioning of the reclamation system in subsequent months [40-43].

April was characterised by a change in the operating regime. The efficiency coefficient decreased to 0.30, and operating time totalled 216 hours. During this period, groundwater deepened to 2.2-2.4 m. The reduction in drainage intensity coincided with the onset of active water uptake by vegetation and a decline in moisture inflow. Maintaining the coefficient at 0.30 ensured preservation of an optimal regime: over-drainage was avoided, and a balance between irrigation input and its removal was maintained. Research materials emphasised that moderate spring values play a regulating role, preventing adverse effects of excessive drainage [44-46]. The summer months were marked by uniform operational parameters. In June, July, and August, operational coefficients remained at 0.25, and operating duration was 180-186 hours. During this period, the groundwater level gradually declined and by August reached a depth of 3.0-3.2 m. According to published data, this depth range is considered optimal for preventing secondary salinisation and maintaining soils in a productive state [47, 48]. The stability of coefficients in summer indicated reliable operation of the drainage system and compliance of operational parameters with reclamation requirements.

In September, a renewed increase in operational activity was recorded. The operational coefficient was 0.25 with an operating time of 186 hours. The groundwater level declined to 3.3-3.4 m, consolidating leaching results and preparing the system for transition to the autumn–winter regime. Research materials noted that early autumn is crucial for preventing a reverse rise in levels and salt accumulation [49]. Maintaining the load at 0.25 enabled additional drainage and created favourable conditions for the subsequent season. Autumn was accompanied by a reduction in operational activity. In October, the efficiency coefficient fell to 0.00 and operating time was 0 hours. The groundwater level was maintained at about 3.5 m. November showed similar indicators: no operation was carried out, and the coefficient was 0.00. Literary sources emphasised that during this period the main factor is natural recharge from atmospheric precipitation, while drainage activation is episodic [50-52].

In December, a new rise in operational activity was observed. The efficiency coefficient increased to 0.50, and operating duration was 372 hours. At the same time, the groundwater level remained at a depth of 3.5-3.6 m. Research materials noted that December activation is explained by the need to compensate for the water balance after autumn precipitation and to maintain the system in an optimal state ahead of spring [53, 54]. Increased coefficients ensured the stability of achieved results and prevented over-wetting [55]. Total annual indicators confirmed stable system performance. The average operational coefficient was 0.30 and total operating time reached 2,616 hours. The groundwater level stabilised within 3.5-4.0 m, corresponding to an optimal reclamation regime. Comparative analysis showed that coefficients of 0.50 and high operating duration ensured intensive drawdown, coefficients of 0.25 promoted stabilisation, and zero values maintained the achieved levels without significant change (Figure 3).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Well operation time, h	372	336	372	216	0	180	186	186	180	0	216	372

Source: compiled by the authors based on [17-19]

Fig. 3: Summary chart of operation and groundwater level drawdown

Thus, vertical drainage operation throughout the year was characterised by pronounced seasonal cyclicality and a clear relationship with groundwater level dynamics. Spring and winter periods were associated with peak operational coefficients of 0.50 and depths up to 3.6 m; summer was stable at 0.25 with depths of 3.0-3.2 m; and autumn showed a reduction in activity to zero values. It was emphasised that maintaining the coefficient at no less than 0.25 is a necessary condition for effective drainage performance, whereas values of 0.50 act as key regulators during transitional periods, preventing waterlogging and secondary salinisation.

Discussion

Groundwater depth and vertical drainage operation followed a seasonal pattern. Groundwater reached the soil surface to 1.5–1.7 m before the growing season, indicating high secondary-salinisation risk. After meltwater and irrigation water intake, the rate of shallowing increased from 0.20–0.30 m/day to 0.80–0.90 m/day at the peak and then slowed to 0.10–0.15 m/day. This sequence shows quick aeration zone saturation and hydraulic stabilisation. Groundwater averaged 1.4–1.6 m in spring, 3.0–3.3 m in summer, and 2.6–2.8 m in autumn winter in 2021–2024. A recurring pattern shows that the drainage system responded regularly to seasonal recharge and irrigation. The observed repeatability does not prove that groundwater dynamics were independent of interannual climatic or irrigation variability because climatic and irrigation variables were not directly included in the statistical models.

The drainage system managed to maintain an average discharge of 38 L/s, pump 260-325 thousand m³ each ten-day period, and attain efficiency coefficients of 0.96-0.97. These findings show that pumping performance during leaching was near the design baseline. Reducing the operation length from 10 to 8 days reduced pumped capacity; however, discharge remained unchanged during active pumping. The third ten-day electricity consumption drop was bigger than the operating length and pumped volume reduction, thus it should be interpreted cautiously. It may indicate sporadic pumping, fewer active wells, or a data-recording error; thus, operational logs should be checked before interpreting it as an energy efficiency improvement.

The comparison with [56] illustrates the importance of regional hydrogeological context. Their research concerned coastal basins in Italy, where groundwater seawater interaction and saline intrusion represented major controls on groundwater conditions. In contrast, the present study examined an inland irrigated region in which seasonal recharge, irrigation water, and drainage operation were the principal factors considered. Consequently, the Italian findings should not be used as direct evidence for the numerical groundwater fluctuations observed in Kazakhstan. Their relevance lies instead in demonstrating that drainage performance must be interpreted in relation to the hydrogeological processes specific to each region. The present findings therefore provide region-specific empirical information that cannot be substituted by observations from coastal aquifers.

The present findings correspond conceptually to the conclusions of [57], who identified inadequate zdrainage and shallow groundwater as major factors contributing to irrigation-induced salinity and sodicity. The current results extend these general conclusions by providing operational observations from Southern Kazakhstan. In particular, they demonstrate when critical groundwater conditions occurred during the annual cycle and how drainage operation varied in response. Nevertheless, the present study measured groundwater depth rather than soil or groundwater salinity directly. Therefore, the data support the interpretation that drainage reduced conditions associated with secondary salinisation risk, but they do not independently confirm changes in salt concentration or soil salinity.

[58] Discussed irrigation-system adaptation under water scarcity at a broader policy and resource-management level. The present findings complement that perspective by identifying an operational mechanism through which adaptation may be implemented locally: increasing drainage intensity when groundwater approaches a critical depth and reducing pumping after groundwater stabilisation. The seasonal distribution of operational coefficients showed that drainage requirements were not constant throughout the year. Coefficients of approximately 0.50 were recorded during periods of elevated recharge, whereas values of 0.25–0.30 were sufficient during more stable summer conditions. This relationship supports the use of seasonally differentiated drainage schedules rather than uniform year-round pumping. Unlike the broad scenarios considered in their study, however, the present conclusions are limited to the monitored reclamation sites and should not be generalised to other regions without additional validation.

[59] Examined plant-based adaptation to saline and waterlogged environments, focusing on biological resilience rather than engineered groundwater regulation. The present study demonstrated that seasonal stability can also be achieved

through hydraulic control. Vertical drainage directly reduced shallow groundwater conditions during critical periods and maintained a more stable reclamation regime throughout the annual cycle. Biological reclamation may therefore complement drainage by improving plant and soil resilience, but it cannot replace the hydraulic function of drainage where shallow groundwater is the principal cause of waterlogging and secondary salinisation risk.

[60] Discussed the reclamation and management of sodic soils through drainage, agronomic practices, and salinity-reduction measures but did not provide detailed seasonal groundwater observations. The present study adds region-specific operational evidence by demonstrating a recurring relationship between groundwater depth and drainage-system activity. Groundwater approached the soil surface in spring, declined during summer, and reached relative equilibrium in autumn and winter. Nevertheless, the repeatability of this pattern should not be interpreted as evidence that groundwater dynamics were independent of climatic or irrigation variability, because these factors were not included directly in the statistical models.

[61] Considered algaculture as an alternative approach to restoring land unsuitable for conventional agricultural production. In contrast to this prospective and biologically oriented strategy, the present analysis was based on actual drainage-system records. During the leaching period, operating duration ranged from 8 to 10 days, average discharge remained at 38 L/s, pumped-water volume ranged from approximately 260 to 325 thousand m^3, and the efficiency coefficient remained within 0.96–0.97. These findings show that engineered drainage provided immediate regulation of groundwater depth, whereas algaculture should be regarded as a complementary reclamation measure rather than a direct substitute for groundwater-control infrastructure.

[62] Summarised agronomic and chemical methods for managing soil salt regimes and maintaining agrolandscape productivity. The present results extend this general framework by demonstrating that the timing and intensity of drainage operation are also important components of reclamation management. The recurring alternation between spring groundwater rise, summer drawdown, and autumn winter stabilisation indicates that uniform year-round pumping is unnecessary. Instead, drainage operation can be adjusted according to seasonal groundwater conditions, thereby maintaining the reclamation effect while avoiding excessive energy consumption.

The observed spring rise and summer decline are consistent with the hydrological relationships examined by [63] through modelling of recharge, irrigation infiltration, evapotranspiration, groundwater flow, and drainage outflow. Their approach explained the mechanisms governing water movement, whereas the present study documented how these mechanisms were expressed under actual operating conditions. The sharp spring rise recorded in Southern Kazakhstan indicates a short period in which recharge exceeded drainage removal, whereas the subsequent summer decline suggests that pumping, evapotranspiration, and reduced recharge jointly contributed to groundwater drawdown. Because the study did not separately quantify these water-balance components, their individual contributions cannot be determined.

[64] Emphasised the environmental consequences of intensive irrigation, including salt accumulation, water-quality deterioration, and long-term changes in the soil–water environment. The present findings connect this environmental perspective with the technical operation of vertical drainage. The repeated seasonal adjustment of drainage load kept groundwater depth outside the most hazardous range for much of the year. However, the study measured groundwater depth rather than actual soil salinity; therefore, drainage effectiveness was demonstrated in terms of water-regime regulation, while its direct effect on salt removal remains to be confirmed through soil and groundwater salinity measurements.

[65] Considered hydroponic wastewater treatment and reuse as non-traditional approaches to reducing pressure on land and water resources. These technologies may improve water-use efficiency and support the utilisation of marginal water sources, but they do not perform the same hydraulic function as vertical drainage. Where shallow groundwater represents the main source of waterlogging and salinisation risk, hydroponic systems should therefore be regarded as complementary resource-management measures rather than replacements for groundwater-control infrastructure.

[66] Similarly examined wastewater-treatment and reuse technologies involving engineering and biological filtration mechanisms. Such approaches may support sustainable resource use and reduce freshwater demand, but they do not directly regulate groundwater depth in irrigated saline lands. The current results show that engineered vertical drainage can respond rapidly to seasonal groundwater rise and maintain groundwater within a more favourable depth range. Wastewater-treatment and reuse technologies may therefore supplement conventional reclamation infrastructure but cannot substitute for drainage where direct hydraulic regulation is required.

Overall, the findings agree with previous research in recognising groundwater regulation as a central component of saline-land reclamation, but they add region-specific evidence on the timing and operational intensity of drainage in Southern

Kazakhstan. The principal contribution is not confirmation of the general importance of drainage, which is already well established, but identification of a recurring relationship between seasonal groundwater depth and drainage-system load. Groundwater approached the critical range in spring, drainage intensity increased during periods of elevated recharge, and lower operational coefficients were sufficient after summer drawdown. These observations support groundwater-depth-based adjustment of pumping schedules. However, confirmation of the long-term reclamation effect requires direct soil and groundwater salinity measurements, wider spatial coverage, and more complete reporting of statistical test results.

Conclusion

The study confirmed a stable pattern of seasonal groundwater level dynamics under Southern Kazakhstan conditions and demonstrated the effectiveness of vertical drainage operation under different regimes. At the beginning of the growing season, groundwater was recorded at a depth of 1.5-1.7 m, corresponding to the critical threshold for the development of secondary salinisation processes. As early as days 5-6 after the inflow of irrigation and meltwater, a rapid rise occurred: the rate of change was 0.20-0.30 m/day during the first two days, then reached 0.80-0.90 m/day on the fourth day, after which it stabilised at 0.10-0.15 m/day. These data confirmed the short-term nature of the sharp rise followed by a transition to an equilibrium phase. Analysis of multi-year dynamics (2021-2024) showed repeatability of three stages in the annual cycle: spring shallowing to 1.4-1.6 m, summer deepening to 2.8-3.3 m, and autumn–winter stabilisation at 2.6-2.8 m. Across different years, the fluctuation amplitude ranged from 1.5 to 1.8 m, indicating stability of the rhythm. The spring period remained the most critical, coinciding with the active crop development phase, confirming the need for strict control of the irrigation regime. Operational parameters of drainage well operation during the leaching period also showed high stability. Average discharge was maintained at 38 L/s; the volume of pumped water across ten-day periods ranged from 260.35 to 325.45 thousand m^3; and energy consumption decreased from 4,467.2 to 416.6 kWh. The efficiency coefficient remained within 0.96-0.97, confirming reliable system operation even when operating time was reduced. Further analysis of the operational coefficient revealed a clear seasonal dependence. In spring and early autumn, values reached 0.50; in summer they remained at 0.30; in May, transitional values of about 0.25 were recorded; and in winter the load was reduced almost to zero.

Maintaining the operational coefficient at no less than 0.25 was identified as a condition for stable system performance, while values of 0.50 were required during transitional periods to prevent waterlogging and secondary salinisation. Under comparable hydrogeological conditions, drainage operators should increase the operational coefficient to approximately 0.50 during the spring recharge period and in early autumn, maintain it within 0.25-0.30 during summer, and reduce pumping to a maintenance regime in winter when groundwater remains stable. Groundwater depth should be monitored at ten-day intervals, with drainage activated or intensified when the level approaches the critical range of 1.5-1.7 m. An average discharge of approximately 38 L/s may be maintained during active leaching, while operating duration should be adjusted according to groundwater inflow to avoid unnecessary pumping and energy consumption.

The study has several limitations. First, secondary salinisation risk was inferred from groundwater depth rather than verified through direct measurements of soil or groundwater salinity. Second, the spatial coverage was limited to selected reclamation sites in the Turkestan Region, which restricts the generalisability of the findings to other hydrogeological and irrigation conditions. Third, the statistical reporting was incomplete, as exact test statistics, p-values, confidence intervals, and effect sizes were not consistently presented. Further research should therefore include direct salinity monitoring, expand observations across different regions and soil types, and provide more comprehensive statistical reporting to validate the recommended drainage regimes.

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Author's Contributions

Balzhan Amanbayeva: Conceptualization, methodology, investigation, data curation, write original draft.
Raushan Dzhaisambekova: Methodology, formal analysis, software, visualization.
Alexander Basmanov: Investigation, resources, write review and edited.
Nurlan Balgabayev: Validation, formal analysis, write review and edited.
Rustem Ergali: Conceptualization, supervision, project administration, write review and edited.
All authors have read and approved the final version of the manuscript.

Ethics

Not applicable. The study did not involve human participants, animals, personal data, or biological materials.

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