

Modeling the process of management of water-salt and food regime of salt soils of marginal land using waste water

Zh. Mustafayev^{1,*}, S. Umirzakov², Zh. Baimanov², K. Akylbayev³ and K. Budikova³

¹Department of Landscape Study and Problems of Nature Management, Institute of Geography and Water Security Science Committee, Seifullin av. 458/1, KZ050000 Almaty, Kazakhstan

²Kazakh Scientific Research Rice Growing named after, I, Zhakhaev, Abaya Str. 25b, KZ120000 Kyzylorda, Kazakhstan

³Korkyt-Ata Kyzylorda State University, 29A Ayteke Bi Str., KZ120000 Kyzylorda, Kazakhstan

*Correspondence: z-mustafa@rambler.ru

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Abstract. Following the development and further improvement of the ecosystem approach to the development of saline marginal lands, a theoretical justification has been prepared for the conceptual model of the technology for the management of the salinity and nutritional regime of marginal lands, where the development of such land takes place in three symmetrical and parallel-sequential actions in time at annual intervals on the basis of using biologization of agriculture, programming productivity of agricultural crops with desalinization of the saline soil to a certain acceptable level subject to leaching limit and chemical reclamation, taking into account the environmental management requirements and classification of the saline soil and salt tolerance of agricultural crops. In addition, the distinctive peculiarities of the proposed technology are the possibility to implement the entire complex of environment-forming functions of the natural system, including the assessment of energy resources of the soil and vegetation cover (various agro-ecological categories), productivity of agricultural land using the reference yield methods, water consumption deficit of agricultural land and leaching limits, ensuring the gradual achievement of the safe level of salinity, using the biological characteristics of salt-tolerant crops (halophytes) and chemical reclamation, based on application of gypsum to the topsoil, owing to a balanced supply of mineral fertilizers, and based on their rationing, taking into account planning the yield of cultivated crops. To illustrate the capability of the presented models, a two-year field experiment was conducted on saline lands using wastewater in the Kyzylorda region of the Republic of Kazakhstan and the results showed that supplementing the information with data from actual measurement results will provide even greater adaptability of the model. Based on the experimental research conducted to explore the possibility of managing the water-salt and nutrient regimes of soils in marginal lands using wastewater and salt-tolerant crops, and developed through mathematical models of soil water, salt, and nutrient dynamics along with a control technology algorithm for these natural-technogenic processes, it was demonstrated that the theoretical justification and the proposed conceptual model of the software and hardware system for managing the soil water-salt regime under wastewater irrigation comply with

environmental protection requirements and align with the ecological, economic, and social aspects of the sustainability triad.

The materials and methods of this manuscript, except for the experimental part of the study were presented as a preprint in Research Square (Mustafayev et al., 2024).

Key words: saline soil, marginal land, development technology, salinity management, leaching, gypsum application, irrigation, halophytes.

INTRODUCTION

The strategy for the development of agricultural land reclamation in the countries of the Eurasian region is based on the maximum possible crop yield through the creation of comfortable conditions for plants as objects of reclamation, and has been ensured over the last 50 years through the transformation of agricultural land irrigation standards from biological to reclamation and from reclamation to reclamation-leaching, in quantitative terms exceeding 1.5–2.0 times the evaporation capacity of the natural system. In this context, in areas of insufficient moisture, to drain excess water from the root layer of soil as a prevention of secondary salinization of irrigated land and adjacent territories, and not the causes, while relative to irrigation systems, collector-drainage (drainage) systems were designed, violating the basic principles of agricultural land reclamation ‘...improvement of the hydrothermal regime, acceleration of the biological and deceleration of the geological cycle of water and chemicals...’. As a result, almost all natural processes were dramatically disrupted: the hydrological regime of permanent and temporary watercourses of river systems changed; geochemical flows have increased many times due to the involvement of huge masses of salt, previously ‘buried’ by nature, in the active geological cycle; within the irrigated land and adjacent territories, soil, biological, hydrogeological and ecological processes have changed, as a result, saline and degraded marginal lands have developed, requiring functional-component and structural reconstruction for their reclamation and normalization of their ecological properties.

Purpose of the study is a scientific and methodological justification of the innovative approach and technology for the management of salinization of marginal lands, providing reclamation and normalization of the productivity of natural and hydroagrolandscapes for agricultural use.

To properly understand the goals and objectives of managing salinization of marginal agricultural land, it is necessary to define a system of values and the object of influence, namely, such values are man and his environment, and the object of influence is soil as the main component of the landscape biosphere as a whole and as the key instrument and object of labor in agricultural production.

In order to address the above-mentioned challenges and ensure sustainable productivity of saline soils in marginal lands, we developed a conceptual model for the integrated management of the water-salt and nutrient regimes using wastewater irrigation and gypsum application. This model is based on a combination of chemical and biological reclamation techniques, crop programming, and agroecological assessment tools. The methodological details of this approach are presented in the following section.

There is a large number of works devoted to the development of degraded agricultural land using chemical and biochemical reclamation and leaching in combination with irrigation, among which special mention should be given to works of Kireychева et al. (2014), associated with the development of a fragment of the classifier of methods for the restoration of the fertility of degraded land; and works of Kaziyeв et al. (2021), which presented the created multicomponent tiered agrophytocenoses during vegetative reclamation of desert pastures; works of Bilquees et al. (2003), which present results of seawater irrigation using local halophytes in the desert zone of Pakistan, and the possibility of creating a profitable oil-yielding industry; works of Abass Abdu et al. (2023), which present results of the study on the development of saline land using common soil parameters, and the soil fertility/nutrient/index approach, were employed to estimate the soil quality; while in the works of Shamsutdinov et al. (2009), the concept of biological reclamation during the development of degraded land in desert zones has been formulated. Unsustainable pressure on natural resources threatens the very ecosystem of services on which the global food system depends (Howe et al., 2014), and land degradation is a complicating factor in achieving not only sustainable development but also in increasing the productivity of land resources (Vlek et al., 2017), Mustafayev & Umirzakov (2013) presented the principle of an environmentally safe technology for wastewater utilization in specialized agro-landscapes.

At the same time, the strategy for reclamation of marginal lands and technologies for their restoration should be based on the morphological, physicochemical, genetic and biochemical properties of halophytes (Busby et al., 2017), ensuring their successful growth in saline areas in various climatic conditions and under different degrees of pressure on agricultural soils (Woldeyohannis, 2024), which is a promising environmentally friendly technology for saline lands and based on them, biosalt agriculture can be created (Rahman et al., 2023), using sea and poor-quality water for irrigation, thereby reducing dependence on dwindling freshwater resources (Alkharabsheh et al., 2021).

The works of Mitchell (1968), Kolb (1971), Petrov (1975), Eckholm & Brown (1977), Bresler et al. (1982), Darkoh (1989), Kharin (1992), Chhabra (1996), Ferrero (1996), Gilani (1997), Takamura (1997), Zonn & Kust (1999), Gabunshchina (2001), Petrov (2001), Kust (2002), Kruzhilin & Chasovskikh (2004), Mukhtar & Mustafa (2004), Kulik et al., (2007), Kizyaev (2009), Borodychev et al. (2011), Keller (1923), deal with the problems of prevention of desertification processes and development of degraded soil on the principles of ecological balance of hydro-reclamation, forest-reclamation, and agro-reclamation impacts.

The method of assessing the water-salt balance of irrigated lands has been developed in a broad aspect, and among them it is necessary to note the works of Averyanov (1978), who is the founder of the joint regulation of water, air, thermal, nutrient and salt regimes of the soil, as well as the works of Aidarov, Golovanov & Nikolsky (1990), where the principles of optimizing the meliorative regimes of irrigated and drained agricultural lands are presented, Rex (1995) – system studies of meliorative processes and systems, Borodychev, Dedova, Sozanov and Lytov (2016) – modeling the process of managing the water-salt regime of soils under irrigation conditions, Mustafayev & Abdeshev (2023) – modeling soil salinization and desalinization.

One of the key directions of the technology for the development of saline land is the direction developed in the works of Dedova (2012), associated with the development of a conceptual model for the increase of natural resource potential through complex reclamation and Mustafayev et al. (2015) associated with the formation of a new conceptual approach to the ecosystem substantiation of methods for the development of saline land, based on two symmetrical and parallel-sequential actions in time at annual intervals with desalinization of the saline soil to a certain acceptable level subject to leaching limit, taking into account the environmental management requirements and classification of the saline soil and salt tolerance of agricultural crops (Dedova, 2012; Mustafayev et al., 2015; Mustafayev et al., 2017a; Mustafayev et al., 2024a).

Based on the analysis of the methodological approach for assessing the anthropogenic impact on saline marginal lands within the framework of one of the laws of the materialistic dialectic of ‘negation of negation’, which allows us to improve the natural science understanding of modern ecological and meliorative mechanisms for modeling the water, salt and food regimes of the soil and to study their mutual functioning, under conditions of natural climatic moisture and taking into account meliorative measures (irrigation), including their environmental admissibility, provides a methodological basis for the creation of mathematical tools that ensure comprehensive regulation and management of this natural and man-made process.

MATERIALS AND METHODS

Data analysis. The methodological basis for managing the saline and nutritional regime of saline soils of marginal lands using urban wastewater has become the principles of environmental management, structural modeling of technological processes using biologization of agriculture, ensuring the activation of natural mechanisms for increasing soil fertility, programming the productivity of agricultural crops, based on the development of a complex of interrelated agro technical processes within which it is possible to obtain a calculated yield with a known probability and regulation of the hydrochemical regime of the soil based on the laws of the evolutionary process of the natural system, ensuring environmentally safe desalinization of the soil-forming rock from water-soluble salts by dissolving and carrying them into groundwater when the hydrological regime of the soil changes.

As a basis for the development of the algorithm of the management technology for water-salt and nutritional regimes of the soil on marginal lands, a mathematical model of the integrated fertility index – Pegov & Khomyakov’s (1991) ‘soil index’, consisting of three independent blocks, namely: humus reserves (S_G), mineral reserves (S_{NPK}) and hydrolytic acidity (S_{Hg}), which has the following expression:

$$S = S_G + S_{NPK} + S_{Hg} = [6.4 \cdot (G_{hh} + 0.20 \cdot C_{fh})/600] + 8.5 \cdot \sqrt[3]{N \cdot P \cdot K \cdot \delta} + 5.1 \cdot \exp[-(H_g - 1)/4], \quad (1)$$

where S_G – indicator of the humus impact on the generalized soil index; S_{NPK} – indicator of minerals elements impact (nitrogen, phosphorus and potassium) on the generalized soil index; S_{Hg} – indicator of hydrolytic acidity impact on the generalized soil index; G_{hh} – content of humate humus, t ha⁻¹ or g cm⁻³; G_{fh} – content of fulvic humus, t ha⁻¹ or g cm⁻³; 600.0 – maximum possible humus content in reference (chernozem) soil, t ha⁻¹;

$N = N_i/N_{ont}$; $P = P_2O_{5i}/P_2O_{5ont}$; $K = K_2O_i/K_2O_{ont}$ – relative content of phosphorus and potassium in the soil of agricultural land; N_i , P_2O_5 , K_2O_i – content of nitrogen, phosphorus and potassium in the soil of agricultural land, kg ha⁻¹; N_{ont} , P_2O_{5ont} , K_2O_{ont} – optimal content of nitrogen, phosphorus and potassium in the soil of agricultural land, kg ha⁻¹; $N = N_i/N_{ont}$, $P_2O_5 = P_2O_{5i}/P_2O_{5ont}$, $K_2O = K_2O_i/K_2O_{ont}$ – relative content of phosphorus and potassium in the soil of agricultural land; δ – mineral fertilizer digestion coefficient; H_g – hydrolytic acidity, mg-eq 100 g⁻¹ of soil.

Based on the structural analysis of the mathematical model of the integrated fertility index – ‘soil index’, components of the maximum possible value of the generalized soil index were determined:

– under the conditions of a sufficiently high humus content in the soil, that is, when $(G_{hh} + 0.20 \cdot C_{fh})/600 = 1$, soil index in terms of humus content will be equal to:

$$S_G = 6.4 \cdot (G_{hh} + 0.20 \cdot C_{fh})/600 = 6, \quad (2)$$

– in the absence of a deficiency of mineral reserves in the soil, that is, nitrogen $N = N_i/N_{ont} = 1$, phosphorus $P = P_2O_{5i}/P_2O_{5ont} = 1$ potassium $K = K_2O_i/K_2O_{ont} = 1$ and when the coefficient of mineral fertilizer digestion by plants (δ) reaches one, then the soil index in terms of mineral reserves will be equal to:

$$S_{NPK} = 8.5 \cdot \sqrt[3]{N \cdot P \cdot K \cdot \delta} = 8.5 \cdot \sqrt[3]{1 \cdot 1 \cdot 1 \cdot 1} = 8.5; \quad (3)$$

– with neutral soil acidity, that is $H_g = 1$, the soil index in the presence of neutral acidity will be equal to:

$$S_{Hg} = 5.1 \cdot \exp \left[-\frac{(H_g - 1)}{4} \right] = 5.1 \cdot \exp \left[-\frac{(1 - 1)}{4} \right] = 5, \quad (4)$$

Based on the results of forecast calculations, components of the soil index in terms of humus content (S_G), mineral reserves (S_{NPK}) and hydrolytic soil acidity (S_{Hg}), it is possible to identify the generalized soil index (S): $S = S_G + S_{NPK} + S_{Hg} = 6.4 + 8.5 + 5.1 = 20.0$.

In accordance with the obtained results, weight coefficients of the vegetation productivity (k_i) characterizing the impact of the humus reserve (S_G), mineral reserves (S_{NPK}) and hydrolytic acidity (S_{Hg}) on the soil fertility have been determined (of agricultural crops (Mustafayev et al., 2024b):

$$\begin{aligned} k_{Gi} &= S_G/S = 6.4/20.0 = 0.320; \\ k_{NPKi} &= S_{NPK}/S = 8.5/20.0 = 0.425; \\ k_{Hgi} &= S_{Hg}/S = 5.1/20.0 = 0.255; \end{aligned} \quad (5)$$

$$k_i = k_{Gi} + k_{NPKi} + k_{Hgi} = 0.320 + 0.425 + 0.255 = 1.00,$$

where k_i – weight coefficients of the vegetation productivity characterizing the impact of the humus reserve (S_G), mineral reserves (S_{NPK}) and hydrolytic acidity (S_{Hg}) on the soil fertility.

Consequently, the basic block in the implementation of the technology for the management of salinization of marginal agricultural land is the mathematical model of the integrated fertility index - ‘soil index’, which is produced on the basis of a comprehensive study of all components of nature, based on a systematic approach in comparing the requirements for soil and vegetation cover of agricultural land and their adaptive capabilities with the actual state of natural and technogenic landscapes and the prospect of regulating its properties.

To develop the algorithm of the management technology for salinization of marginal land, it is necessary to create a database of information and analytical materials characterizing their natural and technogenic state:

- climatic indicators, including average monthly temperature (t_i , °C), relative air humidity (α_i , %), annual precipitation (O_{ci} , mm);
- biological index of agricultural crops, including the coefficient of solar energy utilization and removal of mineral reserves from the soil and wastewater by the agricultural crop yield:
 - soil index, including the content of mineral reserves, humate and fulvic humus in the top soil and hydrolytic acidity of the soil;
 - hydrochemical index, including the content of chemical elements in the composition of surface and wastewater.

Thus, the process of biological reclamation of saline marginal lands is based on the quantitative regulation of soil enrichment with organic and mineral fertilizers, aimed at preserving and restoring the natural balance of soil components, while recognizing the importance of the ‘water-soil-plant’ triad. This integration of nutrient management and salinity control implies a comprehensive approach based on the combined application of fertilizers and soil amendments with irrigation water, allowing for fractional delivery of substances in required quantities and at appropriate stages of the growing season, thereby ensuring precise control over the nutrient and salt regimes of the soil.

RESULTS AND DISCUSSION

Based on the development and further improvement of the ecosystem method of development of saline land, technologies for management of the salinity of marginal land have been developed, where the development of saline land takes place in three symmetrical and parallel-sequential actions in time at annual intervals with desalinization of the saline soil to a certain acceptable level subject to leaching limit and chemical reclamation, taking into account the environmental management requirements and classification of the saline soil and salt tolerance of agricultural crops from very highly saline to highly saline, from highly saline to moderately saline, from moderately saline to slightly saline and from slightly saline to non-saline with the subsequent cultivation of corresponding salt-tolerant crops: very tolerant-tolerant-moderately tolerant-moderately sensitive-sensitive.

To address the problems of sustainable management of water-salt and nutrition regimes of the saline soil of marginal land, it is necessary to study the formation of their energy resources and moisture supply, which are a function of the average long-term values of annual precipitation and evaporation from the soil and vegetation surface, reflecting the ratio of heat and moisture characteristic of a given geographical area.

The energy resources of agricultural landscapes are a function of average monthly temperature (t_i , °C) and relative air humidity (α_i , %), expressed by the average annual sum of air temperature above 10 °C ($\sum t_{ci} > 10$ °C), total evaporation from the water surface (E_{oci}) and radiation balance of the daytime surface of the soil and vegetation cover (R_i) (Mustafayev et al., 2024a):

- sum of monthly air temperature ($\sum t_i$): $\sum t_{mi} = t_i \cdot N_i$, where N_i – number of days per month;

- average annual sum of air temperature above 10 °C ($\sum t_{ci} > 10 \text{ °C}$): $\sum t_{ci} > 10 \text{ °C} = \sum_{i=1}^n t_m$, where n – number of months during the period of air temperature above 10 °C;
- monthly evaporation from the water surface, which is determined using Ivanov's formula (1978): $E_{mi} = 0.0018 \cdot (t_i + 25)^2 \cdot (100 - \alpha_i)$, mm;
- total evaporation from the water surface (E_{tmi}): $E_{tmi} = \sum_{i=1}^n E_{mi}$, where n – number of months during the period of air temperatures above 10 °C;
- natural moisture coefficient (C_{mi}): $C_{mi} = O_{ci}/E_{tmi}$;
- radiation balance (photosynthetic active radiation – PAR) of the daytime surface of the soil and vegetation cover (R_i) is determined using Nikolskiy & Shabanov's empirical formula (1986):

$$R_i = 13.39 + 0.0079 \cdot \sum t_{ci} > 10 \text{ °C}, \text{ kcal cm}^{-2} \quad \text{or} \quad (6)$$

$$R_i = 4.1868 \cdot [13.39 + 0.0079 \cdot \sum t_{ci} > 10 \text{ °C}], \text{ kJ cm}^{-2},$$

when using the radiation balance of the daytime surface of the soil and vegetation cover (R_i) it becomes necessary to bring their unit of measurement to kcal ha⁻¹ or kJ ha⁻¹ in further forecast calculations, that is, if 1 ha = 10⁷ cm², then: $R_i = [13.39 + 0.0079 \cdot \sum t_{ci} > 10 \text{ °C}] \cdot 10^8$, kcal ha⁻¹ or $R_i = 4.1868 \cdot [13.39 + 0.0079 \cdot \sum t_{ci} > 10 \text{ °C}] \cdot 10^8$, kJ ha⁻¹.

To determine the value of various agroecological categories of agricultural land productivity, we use Tooming's (1984) reference yield method, which is a logical outcome of the principle of maximum productivity.

The potential yield of agricultural land (PY_i) in ideal conditions is determined using Nichiporovich's formula (Nichiporovich et al., 1961):

$$PY_i = (R_i \cdot 10^8 \cdot K) / (10^2 \cdot q \cdot 10^3 \cdot 10^2) \quad (7)$$

where R_i – amount of photosynthetic active radiation (PAR) during the vegetation period of agricultural crops in a given geographical area, billion kcal ha⁻¹; K – planned PAR utilization factor, %; q – amount of energy released when burning 1 kg of dry matter (calorific value of agricultural crop yield), equal to $q = 4 \cdot 10^3$, kcal; 10² – conversion from kg to centner; 10² – 100% to convert PAR utilization factor to a relative value.

Actual-possible productivity (APP_i , c ha) of agricultural land, subject to limitation of the moisture of soil and vegetation cover by agrometeorological conditions, can be determined using the following formula (Mustafayev et al., 2017b):

$$APP = PY \cdot FW \quad (8)$$

where FW – function of the impact of moisture conditions on crop productivity (moisture coefficient), dimensionless:

$$FW = 1 - [1 - (E_i/E_{opt})]^2 \quad (9)$$

where E_i – total water consumption by agricultural land; E_{opt} – optimal total water consumption by agricultural land.

The expected actual-possible productivity ($EAPP_i$, c ha) of agricultural land on the saline soil of marginal land is limited by the degree of soil salinity:

$$EAPP = APP \cdot \exp[-k \cdot (S_s/S_{per} - 1)^b] = APP \cdot K_s \quad (10)$$

where S_s – salt content in the soil; S_{per} – maximum permissible level of soil salinity, providing the maximum possible productivity of landscapes used for agricultural land; k – parameter characterizing plant response to toxic salts; b – parameter characterizing

the type of soil salinization; $K_s = \exp \left[-k \cdot (S_s/S_{per} - 1)^b \right]$ – coefficient of reduction in agricultural yield due to soil salinization of marginal land (non-saline soil $K_s = 0$; highly saline soil $K_s = 0.25$; moderately saline soil $K_s = 0.75$; slightly saline soil $K_s = 0.80$; non-saline soil $K_s = 1.0$).

By-products of agricultural crops are determined using the formula:

$$C_p = EAPP_0 \cdot \alpha_p = C_b \cdot \alpha_p \quad (11)$$

where $EAPP_0 = C_p$ – main products of agricultural crops, c ha; C_b – byproducts of agricultural crops, c ha; α_p – coefficient characterizing the ratio of the main products of agricultural crops to by-products.

Total water consumption of agricultural land is formed under the influence of the annual radiation balance of the soil and vegetation surface (R_i) and due to the heat spent on evaporation, that is, the result of multiplying the latent heat of vaporization (L) and determined using Budyko's formula (Budyko, 1956):

$$ET_{ci} = 4.1868 \cdot R_i \cdot L^{-1} \quad (12)$$

where L – latent heat of vaporization (kJ cm^{-2} per year per 1 mm of water layer), equal to 2.5 kJ cm^{-3} .

In addition, the maximum permissible water consumption deficit (irrigation rate) of agricultural land is determined taking into account geo-ecological restrictions that have regard to the hydrothermal regime of irrigated land according to the following water balance equation:

$$\Delta E_i = O_{pi} = [4.1868 \cdot (R_i/\bar{R}_i) \cdot L] - O_c \quad (13)$$

where $\bar{R}_i$ – 'radiation dryness index' or hydrothermal coefficient: $\bar{R}_i = R_i/L \cdot AP_i$; AP_{ci} – annual precipitation, mm; O_{pi} – irrigation rate of agricultural land, mm; ΔE_i – water consumption deficit (irrigation rate) of agricultural land, mm.

The ongoing natural changes in global and, consequently, regional climate are manifested through variations in air temperature, which is a function of the evaporative capacity of the natural system and atmospheric precipitation. These parameters characterize the natural moisture conditions of the soil and vegetation cover in both spatial and temporal dimensions.

A retrospective analysis and assessment of spatiotemporal changes in climatic characteristics (air temperature and relative humidity, atmospheric precipitation) are carried out using a hydrometeorological observation database and the trend method. In this context, the value of a climatic variable at a given time is referred to as the level of the climate time series, and the pattern of its evolution over time is described as the trend.

Long-term climatological research shows that air temperature (t_i) and relative humidity (a_i), which describe the evaporative capacity of the natural system (E_o), along with atmospheric precipitation (AP_i), which characterizes the natural moisture of soil and vegetation cover as a dynamic-stochastic process, can be represented by a linear trend equation:

$$t_i = a \cdot T_i + b_i; a_i = a \cdot T_i + b_i; AP_i = a \cdot T_i + b_i \quad (14)$$

where a is the regression coefficient, which shows how much the studied indicator (t_i, a_i, AP_i) depends on the influencing factor (T_i), characterizing the increase or decrease in the value of the time series; b_i is the zero regression coefficient, which shows the minimum value of the studied indicator, in the absence of the influence of the explanatory factor ($T_i = 0$); T_i is the period number or the ordinal number of the year in

the forecasting period or an independent variable.

In Eq. (14), the first terms express the random part of the climate indicators, the last terms express the deterministic part of this process, which is characterized by a tendency that is a function of time, which can serve as a basis for long-term forecasting (for several years ahead).

Based on the equation of the linear trend of the studied (t_i, a_i, AP_i) indicator, it is possible to develop a mathematical model of the absolute growth, growth rate and growth coefficient of the studied indicators, which have a sufficiently high physical and mathematical meaning, based on the law of nature:

- the absolute increase in the studied indicator (AI_i), which shows the quantitative value of any studied indicator (t_{ei}, a_{ei}, AP_i) at the end of the period under consideration (T_{ei}) to its initial value (t_{bi}, a_{bi}, O_{cbi}) at the beginning of the period under consideration (T_{bi}), where, $T_{bi} = 1 = \text{const}$ and is determined by the formula: $AI_i = \alpha \cdot (T_{ei} - 1)$;

- the growth rate of the studied indicator (RI_i) shows the relative value of the absolute growth of the studied indicator (t_i, a_i, AP_i) over the period under consideration, and is calculated using the formula: $RI_i = [\alpha \cdot (T_{ei} - 1)]/T_{ei}$;

- the growth coefficient of the studied indicator (GR_i) is the ratio of the quantitative value of any studied indicator (t_{ei}, a_{ei}, AP_i) at the end of the period under consideration (T_{ei}) to its initial value (t_{bi}, a_{bi}, AP_i) at the beginning of the period under consideration (T_{bi}) and is represented by the following formula: $GR_i = (\alpha \cdot EPUR_i + b)/(\alpha + b)$

When agricultural marginal land is irrigated by wastewater, chemical elements enter the soil layer along with irrigation water, including nitrogen, phosphorus and potassium, enriching agricultural crops with nutrients (Mustafayev & Kemelbekov, 1987):

$$NO_n = n_c \cdot O_{pi}/1,000; PO_{ph} = ph_c \cdot O_{pi}/1,000; KO_{pi} = p_c \cdot O_{pi}/1,000, \quad (15)$$

where n_c, ph_c, p_c – content of nitrogen, phosphorus and potassium in wastewater, mg L^{-1} ; NO_n, PO_{ph}, KO_p – expected amount of nitrogen, phosphorus and potassium entering the wastewater into the soil layer of irrigated land, kg ha^{-1} ; 1,000 – conversion factor from mg L^{-1} to kg ha^{-1} .

The amount of mineral nutrients in the topsoil (0–30 cm) at the beginning of the vegetation period of agricultural crops per 1 ha is determined using the formula:

$$\begin{aligned} NS_i &= 10 \cdot M \cdot n_s = 10 \cdot S \cdot h \cdot d_v \cdot n_s \cdot 10^6 \cdot 10^{-6}; \\ PS_i &= 10 \cdot M \cdot p_s = 10 \cdot S \cdot h \cdot d_v \cdot ph_s \cdot 10^6 \cdot 10^{-6}; \\ KS_i &= 10 \cdot M \cdot p_s = 10 \cdot S \cdot h \cdot d_v \cdot p_s \cdot 10^6 \cdot 10^{-6} \end{aligned} \quad (16)$$

where M – topsoil mass of agricultural land: $M = S \cdot h \cdot d_v \cdot 1,000$, kg ha^{-1} ; 1,000 – conversion factor of dm^3 to m^3 ; S – area 1 ha = $100 \cdot 100 \text{ m}^2$; h – thickness of the topsoil of agricultural land, m; d_v – soil density, kg dm^{-3} ; n_s, ph_s, p_s – content of available forms of nitrogen, phosphorus and potassium in the topsoil, mg 100 per g of soil; NS_i, PS_i, KS_i – reserve of nitrogen, phosphorus and potassium in the topsoil, kg ha^{-1} ; 10^6 – conversion factor from mg to kg , mg kg^{-1} .

Maximum possible mineral reserves in the soil together with wastewater inflow during the vegetation period of agricultural crops cultivated on marginal land is determined using the formula:

$$MPRN_i = NS_i + NO_{pi}; MPRP_i = PS_i + PO_{pi}; MPRK_i = KS_i + KO_{pi} \quad (17)$$

where $MPRN_i, MPRP_i, MPRK_i$ – maximum possible reserves of nitrogen, phosphorus and potassium in the topsoil, kg ha^{-1} .

Use of the maximum possible mineral reserves from the soil by the main and by-products (yield) of agricultural crops is determined as follows:

$$\begin{aligned} NU_i &= MPRN_i \cdot \alpha_{Nmp} + MPRN_i \cdot \alpha_{Nuc}; \\ PhU_i &= MPRP_i \cdot \alpha_{Phmp} + MPRP_i \cdot \alpha_{Phuc}; \\ PU_i &= MPRK_i \cdot \alpha_{Pmp} + MPRK_i \cdot \alpha_{Puc}, \end{aligned} \quad (18)$$

where α_{Nmp} , α_{Phmp} , α_{Pmp} – coefficient of utilization of nitrogen, phosphorus and potassium by the main products of agricultural crops from the topsoil; α_{Nuc} , α_{Phuc} , α_{Puc} – coefficient of utilization of nitrogen, phosphorus and potassium by agricultural by-products from the topsoil; NU_i , PhU_i , PU_i – expected utilization of nitrogen, phosphorus and potassium from the topsoil by the main and by-products (yield) of agricultural crops, kg ha⁻¹.

Total (economic) removal of mineral reserves by the main (B_o) and byproducts (B_c) of agricultural crops is calculated using the formula:

$$\begin{aligned} PRT_i &= B_o \cdot C_{No}/100 + B_c \cdot C_{Nc}/100 \\ RPB_i &= B_o \cdot C_{Pho}/100 + B_c \cdot C_{Phc}/100 \\ RPU_i &= B_o \cdot C_{Po}/100 + B_c \cdot C_{Pc}/100 \end{aligned} \quad (19)$$

where C_{No} , C_{Pho} , C_{Po} – content of nitrogen, phosphorus and potassium in the main products of agricultural crops, %; C_{Nn} , C_{Phc} , C_{Pc} – content of nitrogen, phosphorus and potassium in by-products of agricultural crops, %; PRT_i , RPB_i , RPU_i – possible removal by the main and by-products (yield) of agricultural crops from the topsoil, kg ha⁻¹.

The deficiency of mineral reserves to provide the expected yield of agricultural crops is determined using the expression:

$$\Delta N_i = PRT_i - NB_i \Delta Ph_i = RPB_i - PB_i \Delta P_i = RPU_i - KB_i \quad (20)$$

where ΔN_i , ΔPh_i , ΔP_i – possible removal by the main and by-products (yield) of agricultural crops from the topsoil, kg ha⁻¹.

The rates of mineral fertilization of agricultural land are determined taking into account the content of active ingredients using the formula:

$$\Delta NF_i = \Delta N_i \cdot 100/\alpha_{No}; \Delta PhF_i = \Delta P_i \cdot 100/\alpha_{Pho}; \Delta PF_i = \Delta P_i \cdot 100/\alpha_{Po}, \quad (21)$$

where C_{No} , C_{Pho} , C_{Po} – content of nitrogen, phosphorus and potassium active ingredients in mineral fertilizers, %; ΔNF_i , ΔPhF_i , ΔPF_i – rates of application of nitrogen, phosphorus and potassium in agricultural land, kg ha⁻¹.

For the integrated management of water-salt and food regimes of saline soils of marginal lands, based on the materialistic theory of scientific knowledge and the theoretical-logical concept of the direction and intensity of the cycle within the framework of the law of conservation of matter, equations of water, salt and food balance of the soil layer have been developed:

$$\begin{aligned} \Delta WR_i &= (AP_i + O_{pwi} + O_{pws} + FR_i + ME_{sgwi}) - (E_{tmi} + ME_{gswi}); \\ \Delta GS_{rsi} &= (G_{pwi} + G_{wsi} + G_{api} + SI_{fi} + SF_i) - (RS_{hi} + GS_{rdi} + GS_{sli}); \\ \Delta NR_{si} &= (NW_{ofi} + NW_{mfi} + NW_{wwi} + NI_{sli}) - RN_{wci}, \end{aligned} \quad (22)$$

ΔWR_i – change in soil water reserves over the period under consideration, m³ ha⁻¹; AP_i – total precipitation, m³ ha⁻¹; O_{pwi} – rate of water supply by river water, m³ ha⁻¹; O_{pws} – rate of water supply by wastewater, m³ ha⁻¹; ME_{sgwi} – moisture exchange between soil and groundwater, m³ ha⁻¹; E_{tmi} – total evaporation (evaporability), m³ ha⁻¹; ME_{gswi} – moisture exchange between groundwater and soil water (DD_i – drainage flow), m³ ha⁻¹; FR_i – leaching rate, m³ ha⁻¹; ΔGS_{rsi} – change in salt reserves in the soil over the

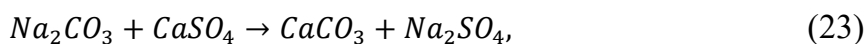
considered period of time, $t \text{ ha}^{-1}$; G_{pwi} – amount of salts supplied with river water, $t \text{ ha}^{-1}$; G_{wsi} – amount of salts supplied with wastewater, $t \text{ ha}^{-1}$; G_{api} – amount of salts supplied with atmospheric precipitation, $t \text{ ha}^{-1}$; SI_{fi} – amount of salts supplied with fertilizers and chemicals, $t \text{ ha}^{-1}$; SF_i – the amount of salts supplied by flushing water, $t \text{ ha}^{-1}$; RS_{hi} – salt removal with the crop, $t \text{ ha}^{-1}$; GS_{rdi} – the amount of salts removed by drainage, $t \text{ ha}^{-1}$; GS_{sli} – the amount of salts in the soil layers, $t \text{ ha}^{-1}$; ΔNR_{si} – the change in the reserves of nutrients in the soil over the period under consideration, kg ha^{-1} ; NW_{ofi} – application of nutrients with organic fertilizers, kg ha^{-1} ; NW_{mfi} – application of nutrients with mineral fertilizers, kg ha^{-1} ; NW_{wwi} – application of nutrients with wastewater, kg ha^{-1} ; NI_{sli} – amount of nutrients in soil layers, $t \text{ ha}^{-1}$; RN_{wci} – removal of nutrients with the crop, kg ha^{-1} .

The equations of water, salt and food balance of the soil layer, reflecting the essence of the teachings of Dokuchaev (1949) and Kostyakov (1951) on the genesis and melioration of soils as a special natural body, allow us to quantitatively assess the direction of cycles, where the most important thing is to establish the relationship between them, since the formation of saline soils of marginal lands is the result of the combined action of climatic, environmental, soil and biological factors.

Increase of the productivity of saline soil of marginal land is possible through the use of special technologies that neutralize acidity and create favorable conditions in the soil for the growth and development of plants.

Theoretical basis of the agrochemical method of increasing the fertility of alkali soil is the restoration of the absorbing soil complex with calcium and the displacement of exchangeable sodium and magnesium. When gypsum is added to the soil, calcium passing into the colloidal complex of alkaline soil causes the coagulation of soil colloids and displaces sodium. Agrophysical, chemical and biological properties of the soil are improved, the displaced sodium (Na) forms a hydrolytically neutral, highly soluble salt with the sulfate anion (SO_4).

The interaction of gypsum with soil is possible according to the following pattern (2021):



Thus, the absorbed sodium ion in the maximum permissible concentration (MPC) is replaced by a calcium ion. The reaction products are harmless in small quantities, however, when application of gypsum to the topsoil containing more than 20% Na in MPC, excess sodium sulfate is formed and it should be leached beyond the root layer after the end of the vegetation period of agricultural land.

It is recommended to calculate the optimal rate of gypsum (ameliorant), taking into account its utilization rate, using the formula (Mustafayev & Abdeshev, 2023):

$$G = [4.3 \cdot 10 \cdot (a \cdot b \cdot d_v \cdot h)]/c \quad (24)$$

where G – gypsum dose, $t \text{ ha}^{-1}$; a – calcium concentration in a saturated gypsum solution, mg L^{-1} ; b – volume of the saturated gypsum solution corresponding to the first coagulation threshold on the dispersion curve; c – soil lot, g ; d_v – soil density, $g \text{ cm}^{-3}$; h – depth of reclaimed layer, cm ; 10 – conversion factor, $t \text{ ha}^{-1}$; 4.3 – gypsum conversion factor:

$$4.3 = (M \cdot CaSO_4 \cdot 2H_2O) / M \cdot Ca \quad (25)$$

where M – molecular weight of $CaSO_4 \cdot 2H_2O$; $M \cdot Ca$ – molecular weight of Ca .

In this case, the dose of gypsum should be agronomically optimal and knowingly safe for the agrocenosis, where the calculation is performed using the formula (Mustafayev & Abdeshev, 2023):

$$S_a = [(MPC - C_c) \cdot M \cdot 10^3] / C_i = [(MPC - C_c) \cdot d_v \cdot h \cdot 10^3] / C_i, \quad (26)$$

where S_a – amount of substance that can be applied, t ha⁻¹; MPC – maximum permissible concentration of an element, mg kg⁻¹; C_i , C_c – content of the element in the ameliorant and in the soil, mg kg⁻¹; M – mass of 1 hectare of topsoil, t ha⁻¹; d_v – soil density, g cm⁻³; h – topsoil thickness, cm.

Under modern conditions, successful implementation of the technology for salinity management on marginal land is possible only with continuous monitoring and timely forecasting of the soil water-salt regime using calculation and analytical methods. For the gradual desalinization of saline soil of marginal land, an effective technique is leaching - the process of step-by-step desalination of the top soil by removal of water-soluble salt into the lower horizons under the influence of small irrigation rates during the vegetation period, where the expected amount of leached salt from the soil layer is determined based on the level of manmade load of the natural system in the annual interval. The value of the required total leaching rate (net) for a meter layer of the soil is calculated according to Mustafayev's method (Mustafayev, 1986), using the formula:

$$N = 1000 \cdot (\alpha/\beta) \cdot \lg(S_H/S_K), N_n = V_t \cdot t \text{ and } t_d = (N - N_p)/K_f, \quad (27)$$

where α – salt release coefficient; S_H and S_K – salt content in the soil at the beginning and end of leaching, %; 1000 – conversion factor from mm to m; K_f – filtration coefficient, m hour⁻¹; N – leaching rate, m³ ha⁻¹; N_p – leaching rate in pressure mode of water absorption into the soil; $N_n = (N - N_p)$ – leaching rate in non-pressure mode of water absorption into the soil; t_d – duration of additional flushing leaching in non-pressure mode of water absorption into the soil, hour; V_t – average rate of water absorption into the soil over a given period of time, m hour⁻¹; n – number of absorption zones; t – duration of leaching; β – acceleration coefficient of the salt release, which depends on the speed of the infiltration flow:

$$\beta = 2.02 \cdot \exp(-9.57 \cdot V_t^b), \quad (28)$$

here V_t^b – speed of the infiltration flow, m hour⁻¹ (Mustafayev, 1986).

The salt content in the soil layer after leaching can be determined using the formula:

$$S_K = S_n \cdot \exp[-(\beta/\alpha) \cdot N_n], \quad (29)$$

The amount of salt removed from the soil layer of marginal land in the annual interval is determined based on the salt balance equation, formed as a result of three symmetrical and parallel-sequential actions of leaching, gypsum application and cultivation of salt-tolerant crops:

$$\Delta S_n + \Delta S_K = S_H - S_K, \quad (30)$$

where ΔS_n – amount of salt removed from the soil layer of marginal land in the annual interval during the leaching process in the vegetation period, t ha⁻¹; ΔS_K – amount of salt removed from the soil layer of marginal land in the annual interval of a salt-tolerant crop, t ha⁻¹.

Thus, the developed algorithm for the technology of management of marginal land salinity based on three symmetrical and parallel-sequential actions, including irrigation-leaching, gypsum application and cultivation of salt-tolerant crops, methodological support, using various models to determine the energy resources of soil and vegetation

cover, water consumption deficit and various agroecological productivity of agricultural land, focused on forecast calculations to determine the necessary elements of mineral nutrition and gypsum application, allow the formation of optimal water-salt and nutrition regimes.

Results of experimental studies

Experimental plot. The experimental site is located within the city of Kyzylorda, in the Tasboget area ($44^{\circ}51'N$, $65^{\circ}31'E$), Kyzylorda region, in the southwest of the Republic of Kazakhstan (Fig. 1), near agricultural fields irrigation. In accordance with the requirement to create environmentally friendly meliorated agricultural landscapes using wastewater, the experimental site consists of two independent sites.

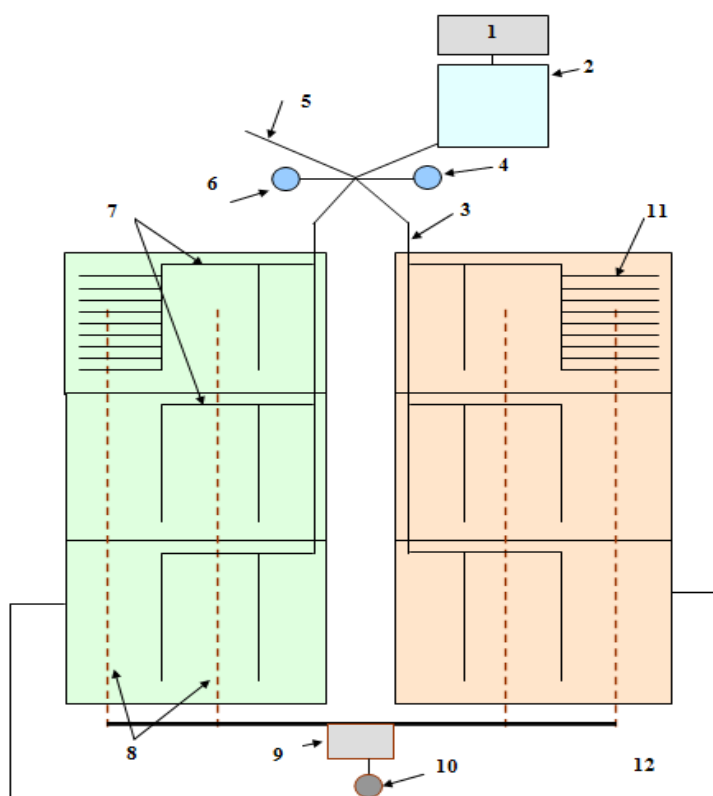


Figure 1. Layout of the experimental site: 1 – treatment facilities; 2 – storage pond; 3 – distribution network for wastewater supply; 4 – distribution network for wastewater supply; 5 – section of distribution channels; 6 – temporary sprinklers; 7 – drainage network; 8 – collector network; 9 – collecting well; 10 – hydraulic structure with a gate; 11 – gate valve; 12 – experimental sites; 13 – buffer zone for non-vegetation disposal of wastewater.

The first site is located within the agricultural fields irrigation, where, using river water, the processes of preserving and restoring the natural balance of soil components will be studied, recognizing the importance of the aspect of the triad ‘water-soil-plants’, and the second site is located outside of agricultural fields irrigation, where the process ‘impact-change-consequences’ on saline marginal lands will be studied using wastewater, for maximum utilization of wastewater based on the evaporative capacity of the natural system (Fig. 1).

Climatic conditions of the experimental site. Kyzylorda region is located to the east of the Aral Sea, in the lower reaches of the Syr Darya River, mainly within the Turan Lowland (elevation 50–200 m), The climate of the city of Kyzylorda is sharply continental with hot, dry, long summers. The tables below show the climate indicators: average monthly temperature (t_i , °C), average monthly relative humidity (α_i , %), monthly precipitation (AP_i , mm) and energy indicators for the sum of air temperatures above 10 °C ($\sum t_{ci}$) > 10 °C, radiation balance of the daytime surface (R_i), total evaporation from the water surface (E_{tmi}) and total water consumption of agricultural lands (ET_{ci}).

To analyze and evaluate the features of the development of climate processes in the experimental site and to determine the energy resources of the natural system, meteorological indicators of the Kyzylorda weather station for 2015–2024 and their fragments for 2020–2024 were used and are presented in Tables 1 and 2.

Table 1. Climate indicators of the experimental site for 2020–2024

Years	Months												Year-old
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Air temperature, °C													
2020	-2.5	1.3	7.0	15.6	23.5	27.2	29.6	26.2	17.9	10.0	-1.4	-11.0	12.0
2021	-8.7	-2.3	3.0	15.7	25.6	28.7	30.4	28.5	19.3	8.6	0.7	-0.3	12.4
2022	-2.1	-0.1	4.5	18.3	22.6	29.4	29.4	26.2	21.4	10.7	3.0	-8.3	12.9
2023	-5.8	-1.2	9.5	15.8	22.8	28.2	31.0	26.8	18.7	12.9	7.8	-1.9	13.7
2024	-4.1	-2.8	5.4	17.6	20.6	29.3	28.0	26.7	18.4	11.5	3.5	-4.0	12.5
Relative air humidity, %													
2020	81	76	51	50	40	28	32	36	41	46	68	78	52.3
2021	72	73	68	43	29	28	32	31	37	50	64	84	50.9
2022	86	79	69	49	42	29	34	34	34	49	73	75	54.4
2023	66	76	57	43	32	28	29	37	48	59	69	70	51.2
2024	80	71	70	44	45	32	42	40	38	60	76	78	56.3
Atmospheric precipitation, mm													
2020	17.8	27.9	0.4	28.5	24.9	3.7	4.2	0.5	0.0	0.4	11.4	1.9	121.6
2021	12.6	19.6	38.3	11.1	0.0	0.9	0.8	0.0	2.7	0.6	13.8	18.9	119.3
2022	18.4	5.9	6.4	12.4	4.3	0.0	2.3	0.5	0.0	5.3	25.5	7.8	88.8
2023	21.1	20.8	15.8	9.7	5.4	4.2	0.9	3.0	0.9	22.1	8.9	7.0	119.8
2024	17.9	4.4	54.1	3.0	42.9	2.4	5.7	3.2	0.7	13.2	17.0	13.0	177.5

Table 2. Energy indicators of the pilot site for 2020–2024

Years	Energy indicators					
	Sum air temperatures ($\sum t_{ci} > 10$ °C)	Radiation balance (R_i), kJ cm^{-2}	Evaporation (E_{tmi}), mm	Evaporation (ET_{ci}), mm	Natural humidification coefficient (C_{mi})	‘Dryness Index’ ($\bar{R}_i$)
2020	4,279.3	197.6	1,617.9	790.4	0.074	6.5
2021	4,530.5	205.9	1,824.6	823.6	0.064	6.9
2022	4,497.2	204.8	1,705.6	819.2	0.052	9.2
2023	4,379.6	200.9	1,701.1	803.7	0.070	6.7
2024	4,293.3	198.1	1,541.8	792.3	0.115	4.5

Analysis of the dynamics of long-term fluctuations in climatic and energy indicators of the Kyzylorda meteorological station for 2015–2024 using the trend method in the Microsoft program Excel produces linear trend equations that show:

- $t_i = 0.0934 \cdot T_i + 11.915$, with a determination index (R^2) of 0.1445, where the trend in the change in average annual air temperatures (t_i , °C) for the period under review is positive, observed from 10.89 to 12.90 °C, the absolute increase is – ‘+’ 0.841 °C, the growth rate is ‘+’ 0.0840 °C and the growth coefficient is 1.070;

- $a_i = -0.3273 \cdot T_i + 55.940$, with the determination index (R^2) of 0.1726, where the trend of change in the average annual relative air humidity (α_i , %) for the period under review is negative, observed from 50.90 to 58.20 °C, the absolute increase is – 2.946%, the growth rate is – 0.295% and the growth coefficient is 0.947;

- $AP_i = -7.6721 \cdot T_i + 189.610$, with the determination index (R^2) of 0.2876, where the trend of change in annual atmospheric precipitation (AP_i , mm) for the period under review is negative, observed from 88.80 to 233.90 mm, the absolute increase is – 69.049 mm, the growth rate is – 6.095 mm and the growth coefficient is 0.620;

- $\sum t_{ci} > 10^\circ\text{C} = 17.379 \cdot T_i + 4,202.2$, with the determination index (R^2) of 0.1605, where the tendency of change in the sum of air temperatures above 10 °C ($\sum t_{ci} > 10^\circ\text{C}$), for the period under review, positive, observed from 4,023.8 to 4,497.0 °C, absolute growth is – ‘+’ 156.411 °C, growth rate is – ‘+’ 15.641 °C and growth coefficient is 1.037;

- $R_i = 0.5752 \cdot T_i + 195.070$, with the determination index (R^2) of 0.1604, where the trend of change in the radiation balance of the daytime surface (R_i), for the period under review is positive, observed from 189.120 to 204.810 kJ cm⁻², the absolute increase is – ‘+’ 5.177 kJ cm⁻², the growth rate is ‘+’ 0.518 kJ cm⁻² and the growth coefficient is 1.026;

- $E_{tmi} = 10.894 \cdot T_i + 1,572.1$, with the determination index (R^2) of 0.1217, where the trend of change in total evaporation from the water surface (E_{tmi}) for the period under review is negative, observed from 1,488.6 to 1,824.6 mm, the absolute increase is – ‘+’ 98.046 mm, the growth rate is ‘+’ 9.804 mm and the growth coefficient is 1.062.

Thus, the analysis of the dynamics of climate and energy processes at the Kyzylorda weather station showed that they are characterized not only by a stochastic component, but also by a deterministic component in the form of multidirectional (positive and negative) trends, which are a function in time. Summarizing the above results, we can conclude that the climate indicators characterizing energy resources are increasing, and the indicator of natural moisture of the soil and vegetation cover is decreasing, which contributes to an increase in the water demand of agricultural lands.

Soil conditions of the experimental area. The conducted studies of chemical composition of saline soils of Tasboget experimental area show predominance of such cations as calcium, magnesium, sodium, potassium and anions of chlorine, sulphate-anions, hydrocarbonates (Table 3).

Soils of the experimental area at the depth of 0–20 cm and 20–40 cm by mechanical composition belong to sandy loam with slightly and moderately saline, chloride-sulphate type of salinization, Soils from 40 to 100 cm are medium loam with very strongly saline, sulphate type of salinization. Hydrogen index by depth of soil layer varies from 8.10 to 7.40, which refer to alkaline environment.

Table 3. Chemical and physico-chemical composition of soils

Name of indicators, unit of measurement	Depth, cm				
	0–20	20–40	40–60	60–80	80–100
Nitrogen (N), mg kg ⁻¹	2.8	2.8	4.2	2.8	2.8
Mass fraction P ₂ O ₅ in soil, mg kg ⁻¹	7.2	9.2	14.8	16	13.6
Mass fraction K ₂ O in soil, mg kg ⁻¹	20	14	26	26	26
Humus, %	1.21	1.519	2.64	2.865	1.32
Dense residue, %	0.389	0.501	1.908	1.961	1.821
Hydrogencarbonate (HCO ₂), %	0.018	0.012	0.018	0.018	0.012
Chlorine (Cl), %	0.099	0.089	0.099	0.053	0.043
Chlorine (Cl), mg-eq per 100 g of soil	2.8	2.5	2.8	1.5	1.2
Sulphate (SO ₂), %	0.173	0.254	1.08	1.210	1.210
Sodium (Na), %	0.012	0.005	0.012	0.012	0.012
Calcium (Ca), %	0.05	0.12	0.495	0.485	0.37
Magnesium (Mg), %	0.037	0.021	0.204	0.183	0.174
Hydrogen index (pH)	8.1	7.9	7.4	7.7	7.6
Salinisation type	Chloride-sulphate		Sulphate		
Degree of salinisation	Lightly saline	Medium saline	Very highly saline		
Mechanical composition	sandy loam	sandy loam	medium sandy loam		

Wastewater and surface water quality indicators. The total estimated volume of wastewater generation for the city of Kyzylorda is 31.1 thousand m³ per day or 11,351.5 thousand m³ per year. The capacity of the modular biological treatment plant in Tasboget settlement is up to 6,400 m³ per day, In the node of wastewater treatment for irrigation of agricultural land is provided for their treatment using activated carbon, Qualitative composition of wastewater of Kyzylorda city in filtration fields and wastewater treatment unit is given in Table 4.

Table 4. Qualitative indicators of wastewater before and after treatment with activated carbon

Name of indicators, unit of measurement	Wastewater quality indicators		Ground water	River water
	before cleaning	after cleaning		
Colour, degree	600.0	510.0	-	-
Hydrogen index (pH)	8.05	7.65	7.50	7.20
Total hardness, mg-eq dm ⁻³	8.10	7.80	-	-
Alkalinity, mmol dm ⁻³	11.20	10.60	-	-
Ammonium (by nitrogen) (NH ₄), mg dm ⁻³	20.90	19.90	-	0.020
Calcium (Ca), mg dm ⁻³	60.0	6.00	0.210	1.340
Magnesium (Mg), mg dm ⁻³	62.4	32.40	0.099	42.20
Total iron (Fe), mg dm ⁻³	2.3	1.40	-	-
Copper (Cu), mg dm ⁻³	0.9	0.60	-	-
Aluminium (Al), mg dm ⁻³	48.7	32.30	-	-
Sulphates (SO ₄), mg dm ⁻³	0.27	0.20	0.436	382.4
Chlorides (Cl), mg dm ⁻³	45.0	10.80	0.150	124.0
Nitrates (NH ₂), mg dm ⁻³	0.33	0.31	-	0.008
Nitrates (NH ₃), mg dm ⁻³	0.146	0.143	-	0.120
Carbonates (Ca), mg dm ⁻³	48.0	36.0	-	-
Hydrocarbonates (HCO ₃), mg dm ⁻³	524.6	512.4	0.866	1.340
Total mineralization (dry residue), g L ⁻¹	2.04	1.61	2.625	-

According to the quality composition of wastewater after the use of activated carbon and groundwater is suitable only for irrigation of special salt-tolerant fodder crops. In this regard, four levels of preparation of irrigation water were used in the study: wastewater after the use of activated carbon; mixing of wastewater after the use of activated carbon with groundwater at 1:3; groundwater (clean) water; river water.

Selection of salt-tolerant crops for cultivation on saline lands using mineralised wastewater and groundwater. For the experimental study, taking into account the soil and climatic factors of the experimental plot, more salt-tolerant forage crops were selected: barley, oats, alfalfa, sweet sorghum, mogar. African millet, corn, as well as from woody plantations: ash and poplar. Using the programmed yield theory, the productivity categories of some agricultural crops were scientifically substantiated taking into account interrelated climatic and agrotechnical factors (Tables 5 and 6),

Table 5. Projected productivity of agricultural crops by Kyzylorda region

Indicators	Agricultural crops, c ha			
	Barley	Oats	Sugar sorghum	Alfalfa
Pphotosynthetic active radiation (PAR) (R_i), kJ cm^{-2}	115.4	115.4	153.6	201.5
Planned PAR efficiency, %	1.0	1.0	2.0	1.5
Caloric value of crop biomass, (kJ kg^{-1})	18,506.0	18,422.0	16,328.0	21,771.4
Potential productivity (Pp_i), kg ha^{-1}	62.4	62.6	366.0	138.8
Climate indicator (FW)	1.0	1.0	1.0	1.0
Really-possible productivity (RPp_i) c ha	62.4	62.6	366.0	138.8
Soil reclamation indicator (K_s)	0.75	0.75	0.75	0.75
Expected productivity (EP_i), c ha	46.8	47.0	274.5	104.1
By-productivity coefficient (α_p)	0.83	0.83	0.67	1.00
By-productivity (U_p), c ha	38.8	39.0	183.9	104.1

The dependence of yield on salinity type and nutrient content is taken into account when calculating the level of expected productivity by introducing reduction coefficients for different soil availability of these elements into the calculation.

Table 6. Dose of mineral fertilizers for programmed harvest of alfalfa for hay according to nutrient removal

Indicators	Doses of mineral fertilisers		
	N	P_2O_5	K_2O
Productivity of agricultural crops, c ha	104.1		
Nutrient removal from the soil by one centner of yield, kg	2.6	0.65	1.50
Total nutrient removal by crop, kg ha^{-1}	270.7	67.7	156.2
Soil nutrient content, mg per 100 g	2.8	7.2	20.0
Nutrients contained in the arable horizon (20 cm), kg ha^{-1}	39.0	266.4	740.0
Nutrient uptake rate from soil	0.53	0.14	0.16
Amount of nutrients received by plants from the soil	20.7	37.3	118.4
Nutrient content in wastewater, mg L^{-1}	16.0	6.0	17.0
Irrigation rate, $\text{m}^3 \text{ha}^{-1}$	8,100.0		
Amount of nutrients delivered with wastewater, kg ha^{-1}	129.6	48.6	137.7
Amount of nutrients received by plants from wastewater, kg ha^{-1}	32.4	12.2	34.4
Dose of mineral fertilizers to be applied to the soil, kg ha^{-1}	217.6	18.2	3.4

In order to obtain a given programmed yield, it is necessary to apply optimal rates of fertilisers to the crop, taking into account its biological characteristics, whose participation in obtaining a given productivity sometimes reaches 60–70%, as well as meeting the needs of plants in nutrients while maintaining and further improving the effective soil fertility and ensuring environmental protection.

Formation of the water-salt regime of the soil under conditions of irrigation with waste and river waters. For irrigated agriculture, in conditions of optimal water supply for sowing agricultural land, the irrigation regime for agricultural crops is determined based on ensuring water demand, taking into account the climatic features of the year, based on the equation of the water balance of the soil layer of irrigated lands (Table 7).

Table 7. Water balance of the soil layer of the experimental plot of irrigated lands with wastewater and river waters during the cultivation of alfalfa

Years	Water balance indicators of the soil layer of the experimental plot							ΔWR_i , m ³ ha ⁻¹
	Reception area				Expenditure part			
	O_{ci} , m ³ ha ⁻¹	A_{pi} , m ³ ha ⁻¹	FR_i , m ³ ha ⁻¹	Sum, m ³ ha ⁻¹	E_{oi} , m ³ ha ⁻¹	DD_i , m ³ ha ⁻¹	Amount, m ³ ha ⁻¹	
Lucerne fields irrigated with wastewater								
2020	1,216.0	13,022.0	4,000.0	18,238.0	14,561.1	3,366.9	17,928.0	310.0
2021	1,193.0	14,863.0	4,000.0	20,056.0	16,421.4	3,314.6	19,736.0	320.0
2022	888.0	14,121.0	4,000.0	19,009.0	15,350.4	3,318.6	18,669.0	340.0
2023	1,198.0	13,772.0	4,000.0	18,970.0	15,309.9	3,305.1	18,615.0	355.0
2024	1,775.0	11,793.0	4,000.0	17,568.0	13,876.2	3,359.8	17,236.0	332.0
Lucerne fields irrigated using river water								
2020	1,216.0	6,688.0	4,000.0	11,904.0	7,904.0	3,748.0	11,652.0	252.0
2021	1,193.0	7,043.0	4,000.0	12,236.0	8,236.0	3,735.0	11,971.0	265.0
2022	888.0	7,304.0	4,000.0	12,192.0	8,192.0	3,765.0	11,957.0	235.0
2023	1,198.0	6,839.0	4,000.0	12,037.0	8,037.0	3,785.0	11,822.0	215.0
2024	1,775.0	6,148.0	4,000.0	11,923.0	7,923.0	3,768.0	11,691.0	232.0

An examination of the water balance structure of an irrigated area where irrigation is carried out using wastewater leads to the conclusion that its incoming part is determined mainly by the irrigation rate (73–75%) supplied during the growing season, and partly by the leaching rate (18–20%) supplied at the end and beginning of the growing season to moisten the soil and remove salts from the active soil layer. At the same time, the outgoing part of the water balance of irrigated areas is the evaporation of moisture from the surface of the soil and vegetation cover (75–77%), and partly from drainage runoff (23–25%) formed during irrigation and leaching of salts from the active soil layer.

Calculation of the water balance of the irrigated area, where irrigation is carried out using river water, based on the totality of its incoming and outgoing components showed that the incoming part consists of the irrigation rate (60–65%) supplied during the growing season and the leaching rate (30–35%) supplied during the non-growing season to moisten the soil and remove salts from the active soil layer. At the same time, the outgoing part of the water balance of irrigated areas consists of moisture evaporation

from the surface of the soil and vegetation cover (65–70%) and drainage runoff (25–30%) formed during irrigation and leaching of salts from the active soil layer.

The methodological basis for studying the formation of the salt regime of the soil of an irrigated area using waste and river water was the information support for the water balance equation of the experimental site using calculation methods (Table 8).

Table 8. Forecasting the salt regime of the soil of the experimental site with irrigation with wastewater and groundwater (using alfalfa as an example)

Years	Water balance indicators of the soil layer of the experimental plot							ΔGS_{rsi} , t ha ⁻¹
	Reception area				Expenditure part			
	G_{opi} , t ha ⁻¹	G_{api} , t ha ⁻¹	SF_i , t ha ⁻¹	Sum, t ha ⁻¹	RS_{hi} , t ha ⁻¹	GS_{rdi} , t ha ⁻¹	amount, t ha ⁻¹	
Lucerne fields irrigated with wastewater								
2020	22.89	0.61	5.40	28.90	0.31	8.14	8.45	20.45
2021	25.85	0.60	5.32	31.77	0.30	7.88	8.18	23.59
2022	23.89	0.44	5.48	29.81	0.30	7.81	8.11	21.70
2023	26.20	0.60	5.76	32.56	0.30	9.04	9.34	23.22
2024	26.26	0.89	5.84	32.99	0.30	10.47	10.77	22.22
Lucerne fields irrigated using river water								
2020	11.07	0.61	5.40	17.08	0.31	7.62	7.93	9.15
2021	11.53	0.60	5.32	17.45	0.32	7.38	7.70	9.75
2022	11.47	0.44	5.48	17.39	0.33	7.68	8.01	9.38
2023	11.25	0.60	5.76	17.61	0.33	8.16	8.49	9.12
2024	11.09	0.89	5.84	17.82	0.34	8.28	8.62	9.20

To ensure increased productivity of agricultural lands on saline lands with relatively low natural moisture, one of the effective methods is the moisture-charging-leaching technology, aimed at: firstly, moistening the soil layer before sowing agricultural crops, and secondly, desalination of the upper soil layer (0–40 cm), the accumulated process of irrigation of the growing season, due to the removal of water-soluble salts to the lower horizons under the influence of large irrigation rates.

Analysis and assessment of the salt regime of the soil of irrigated areas using wastewater and river water showed that the soil and climatic region taken for the study is characterized not only by high mineralization of wastewater, but also river water. Under such conditions, in irrigated areas using wastewater, salts are constantly accumulating in the active soil layer, and where river water is used in irrigated areas, due to high mineralization, their desalting effect of the active soil layer is very low. Based on the above, we can conclude that the expected amount of precipitation does not provide natural washing of the active soil layer, and the available surface and wastewater, due to sufficiently high mineralization, do not have sufficient capacity for desalination of soil prone to secondary salinization. Under these conditions, widespread use of biological reclamation technology of saline marginal lands using salt-resistant crops can ensure effective productivity of agricultural land.

Assessment of soil fertility based on agrochemical indicators under conditions of irrigation with wastewater and river water. The assessment of the main ecological functions of soils is based on the reserves and composition of humus (humic and fulvic humus), reserves of the main elements of mineral nutrition (nitrogen, phosphorus,

potassium) and acid-base indicators (pH and hydrolytic acidity), and as an integral indicator for assessing soil fertility, one can use the ‘soil index’ [30], which varies from 0 to 20 units (0–4.00 – very low; 0.41–8.00 – low; 8.01–12.00 – average; 12.01–16.00 – high; 16.01–20.00 – very high).

To analyze and evaluate the agrochemical fertility index of agricultural lands irrigated using waste and river water, an information and analytical research base has been created for the ‘dryness index’ ($\bar{R}_i$), soil hydrolytic acidity (H_g), fertilizer assimilation coefficient by plants (δ_i), humus reserves (G_i), relative content of nitrogen (N_i/N_{max}), phosphorus (P_i/P_{max}) and potassium (K_i/K_{max}), the ratio of humates to fulvates (G_{hh}/G_{fh}), based on experimental data obtained in pilot production sites in the area of the village of Tasboget in the Kyzylorda region of the Republic of Kazakhstan (Table 9).

Table 9. Information and analytical base for assessing the ‘soil index’ in irrigated areas of the pilot production site in the area of the village of Tasboget, Kyzylorda region, Republic of Kazakhstan

Years	‘Dryness Index’ ($\bar{R}_i$)	Humus reserves, %	Ratio of humates to fulvates (G_{hh}/G_{fh})	Nutrient availability as a percentage of maximum value			δ_i	H_g , mg-eq/100 g ⁻¹ of soil
				N_i/N_{max}	P_i/P_{max}	K_i/K_{max}		
Lucerne fields irrigated with wastewater								
2020	6.5	1.41	1.683	0.221	0.099	0.433	0.98	8.10
2021	6.9	1.45	1.610	0.236	0.103	0.444	1.19	7.90
2022	9.2	1.48	1.493	0.246	0.106	0.452	1.93	7.40
2023	6.7	1.52	1.598	0.260	0.111	0.462	1.45	7.70
2024	4.5	1.61	1.639	0.292	0.120	0.485	1.59	7.60
Lucerne fields irrigated using river water								
2020	6.5	1.640	1.966	0.302	0.123	0.493	2.06	7.33
2021	6.9	1.645	1.911	0.304	0.124	0.494	2.34	7.20
2022	9.2	1.654	1.718	0.307	0.125	0.496	2.79	7.02
2023	6.7	1.659	1.845	0.308	0.126	0.498	2.39	7.18
2024	4.5	1.662	1.807	0.309	0.126	0.498	2.23	7.25

Based on the information and analytical base of the study (Table 9), the assessment of the integral fertility indicator – the ‘soil index’ of the experimental production site was carried out using an automated spreadsheet based on Microsoft Excel, which is shown in Table 10.

An assessment of the soil fertility indicator – the ‘soil index’ in irrigated areas of pilot production sites in the area of the village of Tasboget in the Kyzylorda region of the Republic of Kazakhstan based on the main agrochemical indicators (humus reserves, reserves of mineral nutrients and hydrolytic acidity) for the period 2020–2024 showed:

- in alfalfa fields where irrigation was carried out using wastewater, the indicator of the influence of humus on the generalized soil index (S_G) varies from 2.10 to 2.41 units, the indicator of the influence of mineral nutrition elements (nitrogen, phosphorus and potassium) on the generalized soil index (S_{NPK}) – from 1.79 to 2.55 units, the indicator of the influence of hydrolytic acidity on the generalized soil index (S_{Hg}) – from 0.88 to 1.05 units, and the ‘soil index’ – from 4.77 to 5.96 units and, in general, characterizes a low level of soil fertility;

– in alfalfa fields, where irrigation was carried out using river water, the indicator of the influence of humus on the generalized soil index (S_G) varies from 2.41 to 2.46 units, the indicator of the influence of mineral nutrition elements (nitrogen, phosphorus and potassium) on the generalized soil index (S_{NPK}) – from 2.85 to 3.19 units, the indicator of the influence of hydrolytic acidity on the generalized soil index (S_{Hg}) – from 1.07 to 1.15 units, and the ‘soil index’ – from 6.33 to 6.80 units and, in general, characterizes a low level of soil fertility.

Table 10. Integral indicators of soil fertility – ‘soil index’ in irrigated areas of the pilot production site in the area of the village of Tasboget, Kyzylorda region, Republic of Kazakhstan

Years	Soil index values			‘Soil Index’ (S_i)
	S_{Gi}	S_{NPKi}	S_{Hgi}	
Lucerne fields irrigated with wastewater				
2020	2.10	1.79	0.88	4.77
2021	2.17	1.99	0.93	5.09
2022	2.24	2.41	1.05	5.70
2023	2.28	2.28	0.97	5.53
2024	2.41	2.55	1.00	5.96
Lucerne fields where irrigation is carried out using river water				
2020	2.41	2.85	1.07	6.33
2021	2.42	2.99	1.10	6.51
2022	2.46	3.19	1.15	6.80
2023	2.45	3.05	1.11	6.61
2024	2.46	2.98	1.09	6.53

Thus, the conducted analysis of the state of agricultural lands based on agrochemical indicators using the ‘soil index’ showed that the reserve of humus and the main elements of mineral nutrition is quite low and requires a set of reclamation measures to increase soil fertility.

CONCLUSIONS

Based on the study, theoretical justification and a conceptual model was proposed for the technology of salinity management of marginal land to address problems of managing the soil water-salt and nutritional regimes, built on a mathematical model of the integrated fertility index – ‘soil index’, the distinctive peculiarities of which are as follows:

– possibility to implement the entire complex of functions of the technology of salinity management of marginal land, focused on increase of the ‘soil index’, based on humus reserves (S_G), mineral reserves (S_{NPK}) and hydrolytic acidity (S_{Hg}), using as an alternative to the calculation method using agroclimatic information to predict energy resources, water consumption deficits and various agroecological productivity of agricultural land;

– simultaneous use in combination of different estimated dependencies to assess the need of agricultural crops in nutrients, as well as chemical and biological reclamation and leaching of saline soil, providing the gradual achievement of environmentally safe level of salinization of the soil root layer and their use to adapt calculation models for

predicting water-salt and nutritional regimes, taking into account the natural characteristics of marginal land;

- the developed algorithm for the technology of salinity management of marginal land, including chemical reclamation and leaching, together with the cultivation of salt-tolerant crops serving as an instrument for salt removal from the root layer of the soil is not only limited to the desalinization effect, but also provides high-quality biological products of agricultural land, which create the prerequisites for meeting the needs of agriculture (feed base), food security and environmental sustainability of the region.

The presented analysis of the formation of soil fertility in agricultural lands allows us to determine the direction of the technology for managing salinization of marginal lands, allowing us to restore and increase soil fertility for agricultural use:

- the indicator of the influence of humus on the generalized soil index (S_G) varies from 2.10 to 2.46 units, where an increase in the humus reserve in the soil of marginal lands can be achieved by additional input of soil biomass in the form of by-products of the plant cover;

- the indicator of the influence of mineral nutrition elements (nitrogen, phosphorus and potassium) on the generalized soil index (S_{NPK}) varies from 1.79 to 3.19 units, an increase in the content of mineral nutrition elements in the soil can be achieved through an increase in humus reserves and a balanced supply of organic and mineral fertilizers, based on their standardization taking into account the planning of the yield of cultivated agricultural crops;

- the indicator of the influence of hydrolytic acidity on the generalized soil index (S_{Hg}) varies from 0.88 to 1.15 units, an increase in the value of the soil index for hydrolytic acidity can be achieved by carrying out chemical melioration to obtain a neutral soil reaction;

- the ‘soil index’ varies from 4.47 to 6.80 units and, in general, characterizes a low level of soil fertility; an increase can be achieved using a set of reclamation measures that can increase soil fertility.

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