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RESEARCH ARTICLE
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Influence of Flooding On Soil Properties and the Agrobiological Indicators of Natural Herbage in the Farmlands of West Kazakhstan

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ABSTRACT

Flooded agricultural lands in the arid areas of the West Kazakhstan Region serve as a reliable source of high-grade fodder, the shortage of which impedes the development of livestock breeding. The use of the region's permanent water sources to flood agricultural lands secures the production of grass fodder regardless of weather conditions. Therefore, the study aims to identify the optimal flood regime to enhance the productive parameters of the soil. The methods of chemical analysis and quadrant sampling were applied to establish changes in soil pH, humus content, NO_3, P_2O_5, and K_2O, and the species composition of plots under different flood regimes. Results showed that greater flooding volumes were significantly associated with higher agrochemical indicators in the uppermost soil layer, with humus ranging from 2.8–3.7% ($P<0.05$), nitrate nitrogen 6.3–6.78mg/kg (±0.2), and mobile phosphorus 53.2–74.3mg/kg (±1.5). The only exception was mobile potassium, which increased only with the flooding volume of 4,000–4,500m³/ha, reaching 680.6±5.3mg/kg. Exchangeable sodium content was more favorable for soil fertility at irrigation rates of 3,500–4,000 and 4,000–4,500m³/ha. Flooding volumes over 3,000m³/ha supported optimal soil salinity. Plant density per m² also increased with higher flood volumes. The natural herbage was dominated by couch grass, which reached a density of 269.5 to 374.2units/m² and a share of 93.2–97.8% (of the total number of plants) in flooded areas and 101.8units/m² and 43.3% in the non-flooded area (control). The highest average yield across the study years was achieved at flooding volumes of 4,000–4,500 m³/ha (27.2 cwt/ha) and 3,500–4,000 m³/ha (25.0 cwt/ha), exceeding the control by 253.2% and 224.7%, respectively ($P<0.05$). As a result, the study establishes 3,500–4,500 m³/ha as the optimal flooding regime for improving soil fertility and forage yield in semi-arid West Kazakhstan. These findings can inform irrigation management strategies in other arid and semi-arid regions, where similar flood-based practices could be adapted to enhance soil quality and fodder production.

Keywords: Flooding; Flooding volume; NDWI; Soil; Humus; Soil salt composition; Vegetation species composition; Yield.

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INTRODUCTION

Flood inundation is one of the oldest and most widely used irrigation methods (Cui et al., 2019). Flooding of agricultural land is used universally across continents as a cheap and efficient irrigation technique. Soil flooding leads to significant changes in the content of nutrient elements. Regulated flooding enhances the mobility of nitrogen, phosphorus, and potassium by increasing soil water holding capacity (Gueye et al., 2023). Similar results were observed by Tomasek et al. (2019), who found that the flooding of organic soils contributed to the formation of nitrous oxide production hotspots. Rupngam & Messiga (2024) noted that flooding increases the content of dissolved organic carbon, which is connected with anaerobic conditions and organic matter decomposition.

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Lewis et al. (2014) investigated the effects of flooding and increased temperatures on organic matter mineralization in mangrove forests and salt marshes. Their findings revealed that water saturation in soils suppresses short-term carbon mineralization, reducing CO_2 release by approximately 65% when soil moisture increased from 75% to 85%. This indicates that prolonged flooding may decelerate the decomposition of organic matter, thereby promoting its accumulation in soils. In parallel, Franzluebbers (2002) examined the role of organic matter in soil physical properties, concluding that it enhances soil structure, increases aggregation, and reduces compaction, which collectively improve water infiltration. This relationship is particularly relevant in the context of flooding, as improved soil structure not only influences water distribution but also enhances the capacity of soils to retain organic matter. Together, these studies highlight a synergistic interaction: while flooding slows down organic matter decomposition, the presence of organic matter itself contributes to a soil environment more resilient to waterlogging and conducive to long-term carbon storage.

Stavi et al. (2021) demonstrated that flooding improves soil structure and reduces sodic salinization by flushing out salts and reducing the concentration of exchangeable sodium. Flooding has also been found to alter redox conditions and the acid-base balance (pH) of the soil. According to Sun et al. (2007), exposure to anaerobic conditions decreases pH and increases the mobility of heavy metals, such as cadmium and lead. These changes are important for improving plant growth conditions, especially in acidic soils. Hailegnaw et al. (2023) described the ecological aspects associated with changes in soil pH. These parameters are critical for the mobilization of nutrients and toxic compounds under flooding conditions. Several researchers (Ji et al., 2021; Cheng & Li, 2021; Tjaija, 2022; Zenebe et al., 2022; Hailegnaw et al., 2023; Rupngam & Messiga, 2024;) outline the ecological effects of flooding, which includes reduced soil erosion, improved soil structure, and enhanced fertility. However, these changes depend on the duration of flooding, water quality, and the type of flooding.

Hailegnaw et al. (2023) underscore that proper flooding management can minimize such negative consequences as increased salinization or acidification of soils and optimize the restoration of degraded lands. Furthermore, flooding has a significant influence on the redistribution of anions and cations in soil. As demonstrated by Salmasi et al. (2024), the spreading of water during floods helps leach anions such as chlorides and sulfates from the upper soil horizons, improving conditions for plant growth (Khudair et al., 2024). The availability of calcium, magnesium, and potassium cations increases, which is associated with improved metabolic processes (Koulali et al., 2021; Patel et al., 2021; Kubo et al., 2024; Batool & Afrasiab, 2025). Krzic et al. (2021) noted that flooding stimulates reduction processes, changing the composition of cations and reducing the concentration of sodium in saline soils. These changes have a positive effect on soil structure and its water permeability. To increase fodder production, it is essential to increase soil moisture reserves by optimizing flooding regimes, maintain a normal ecological situation, and create a sustainable, highly productive phytocenosis (Bruinsma, 2012; Shamsutdinov et al., 2013; Nasiyev et al., 2019; Andrés et al., 2020). With a suitable flooding regime, it is possible to increase the abundance of valuable plants on flooded lands (Ongayev et al., 2016; Sketch et al., 2020; Coulibaly & Zombre, 2024). Many plants can avoid the adverse effects of flooding if important life cycle events are properly timed (Blom & Voesenek, 1996).

Saline water flooding is the main cause of decreasing crop yields and deteriorating soil conditions (Cetin & Kirda, 2003; Quiñones & Ang, 2020; Hui & Tan, 2024). Arid and semi-arid areas are distinguished by higher soil salinity, as most of the land there is subject to salinization (Pitman & Läuchli, 2002; Wang et al., 2008; Qian et al., 2019; Nguyen & Nguyen, 2024). Soil salinization may also be responsible for changes in the species composition of vegetation (Guo et al., 2019; Aimen et al., 2022). Soil salt composition undergoes significant changes as a result of deliberate flooding. Studies show that flooding can reduce soil salinity through sodium and chloride leaching, which is evidenced by the experiments of Furtak et al. (2022), where flooding caused significant reductions in alkalinity and salinity.

A study by de León-Lorenzana et al. (2017) showed that regular flooding of highly alkaline and saline soils significantly reduced electrical conductivity and changed the microbial community. Although pH did not change significantly, the decrease in salts, including sodium, contributed to better conditions for microbial communities. In the irrigation district of the Huanghe River, the soil profile experienced a rise in salinity after irrigation with brackish water (1–3g/l) for 30 years, which grew with higher salt concentrations in irrigation water. It was found that the right lowering of the groundwater table can enhance the soil leaching effect, but too much lowering can lead to insufficient soil moisture and high salt concentrations (He et al., 2024; Mohammed & Abdulhameed, 2024). In the Tarim Basin in southern Xinjiang, China, flood irrigation of cotton fields significantly reduced soil salinity in two layers (0–20 and 20–60cm) as a result of leaching. The salinization of soil by neighboring layers correlated poorly before inundation but increased significantly after, especially in the first 10–15 days (He et al., 2023).

Studies conducted in Yuepuhu County in the southern foothills of the Tien Shan showed a marked decrease in the hydraulic conductivity of saturated soil deeper into the soil profile, indicating a significant variability in permeability. Soils salinized by the chloride-sulfate type predominantly contained potassium (K^+) and sodium (Na^+) as major cations in surface soils. Salinity correlated strongly with the content of calcium (Ca^{2+}) and magnesium (Mg^{2+}). Chloride (Cl^-), sulfate (SO_4^{2-}), K^+, Na^+, and bicarbonate (HCO_3^-) reflected the degree of soil salinity (Liaqat et al., 2023; Ma et al., 2024). Soil structure may inhibit the upward transport of highly mineralized groundwater (Ermagambet et al., 2018), while precipitation and evaporation directly affect leaching and the upward movement of surface soil salt, resulting in an uneven distribution of salts in the soil (Fang et al., 2023; Zhu et al., 2024).

Vuerich et al. (2024) found that deeper floods negatively affect plant diversity and biomass gain. Furthermore, longer periods of inundation are detrimental to plant growth (Mustroph, 2018). Flooding primarily limits the diffusion of gases between the plant and the environment due to physical properties (Armstrong, 1980; Kovalev & Invanishchuk, 1999), leading to a decrease in oxygen concentration and causing hypoxia (Lee et al., 2011; Vashisht et al., 2011). To continuously monitor irrigated lands, it is expedient to apply the method of remote sensing, which gives a holistic picture of ecosystems and helps support resource management (Mantas et al., 2013; Chohan et al., 2023; Movchan et al., 2024). The borders of open water objects can be determined using the Normalized Difference Water Index (NDWI) (Zhu et al., 2022). Studies on flooding have produced mixed results, with different parties highlighting both its benefits and adverse effects. A major research gap in these studies is the lack of confirmation on the direct impact of flood irrigation on crop yield and soil fertility. Most studies speculate about these results due to factors such as the movement of ions, dissolved gases, and improved soil water without testing for the direct impact on crop yield. This study aims to address this gap by empirically investigating how irrigation through flooding can enhance yields and soil fertility in West Kazakhstan. Globally, flooding through irrigation has faced challenges such as the possibility of excess soil moisture and the increased probability that diseases and insect pest eggs can be carried from one part to another (Manda et al., 2021). Mubangizi et al. (2023) concluded that although practices like continuous flooding are not sustainable and may lead to the inefficient application of water resources, for arid regions, the application of alternate flooding can greatly influence water management and reduce the risk highlighted by Manda et al. (2021). In Kazakhstan, the application of irrigation through flooding is not well researched, with more focus directed towards the recovery of abandoned lands through flooding and its impact on soil salinity (Laiskhanov et al., 2023). This research aims to highlight the potential for flooding through irrigation, a more accessible method for farmers in semi-arid regions.

The agro-industrial complex of West Kazakhstan prioritizes livestock breeding, which in turn depends on a stable fodder base (Nasiev & Eleshev, 2014; Nasiyev et al., 2020, 2023; Kozhanov et al., 2023). This region contains most of the artificially flooded agricultural lands in the Republic of Kazakhstan, supported by eight large irrigation-and-watering systems covering more than 260 thousand hectares. Floodwater inundation of agricultural lands is considered a cost-efficient and reliable strategy for securing stable yields of forage grasses (Aitzhanova & Zhaparova, 2023; Ongayev et al., 2022, 2023; Karynbayev et al., 2023; Meldebekova et al., 2024). However, the specific yield indicators and plant–soil responses that change under flood irrigation in West Kazakhstan remain insufficiently quantified. To evaluate how flood irrigation influences variation in soil properties and natural herbage parameters in West Kazakhstan. The following were objectives of the study;

• Generate field evidence on the use of flood irrigation to improve forage yield and soil fertility in West Kazakhstan.
• Identify an optimal flooding regime (timing, depth, and duration) to enhance key soil productivity parameters in West Kazakhstan and comparable semi-arid to arid regions.
•Assess the effects of flooding on soil salt composition and salinity, as well as on the species composition, density, and productivity of natural herbage.

MATERIALS & METHODS

Research Subjects and Study Location

Field studies were conducted during 2023–2024 on a seasonally flooded experimental plot in Algabas village, Akzhaik District, West Kazakhstan Region. The site is characterized by weakly solonetzic, heavy loamy chestnut soil with high silt content and low humus. The predominantly flat relief, punctuated by closed, saucer-shaped depressions, promotes water accumulation and periodic inundation. These geomorphic features underpin the high concentration of naturally flooded agricultural lands with meadow vegetation across the West Kazakhstan Region. Flooded agricultural lands of West Kazakhstan Region are located in the Pre-Caspian lowland, which is part of a territory with no drainage due to the absence of groundwater flow gradients (Gumarova et al., 2025). The experimental plots were divided into zones according to the experiment scheme, with different zones receiving different volumes of water (Santos et al., 2023) (Table 1). The experimental plots were divided into five treatments according to the flood volume: no flooding (control), 2500–3000, 3000–3500, 3500–4000, and 4000–4500m³/ha (Table 1). Each treatment was arranged in a randomized complete block design (RCBD) with three replicates, and the plot size for each replicate was 100m². Randomization of treatments was carried out using a random number generator to avoid positional bias across the field.

Table 1: Experiment scheme and coordinates of the centers of experimental plots

No.	Flood volume, m^3/ha	Coordinates WGS 84, (lat.lon)
1	No flooding	50.55815068508392, 50.70610542383932
2	2,500–3,000	50.56017144220143, 50.711038609883055
3	3,000–3,500	50.55939493195679, 50.710437691608675
4	3,500–4,000	50.55800927574779, 50.70845102389081
5	4,000–4,500	50.55610875378727, 50.70812107812203

Research Stages

Experimental Plot Design and Irrigation Control

The mode and frequency of flooding of the studied area prior to the experiment were assessed using field observations and Landsat 8-9 space images of the flooded area taken from the United States Geological Survey website (USGS, 2024). Our investigation of the site surface based on satellite imagery data from Landsat 7, 8, and 9 for the period from 1990 through 2024 showed that the study area experiences annual flooding. To identify and distinguish open water or wet objects on the satellite image against the background of soil and vegetation, we turned to NDWI (Kostikova, 2005; USGS, 2024). NDWI was applied to identify water bodies, clarify their contours on the map, and track changes. NDWI is calculated using the GREEN-NIR (visible green and near infrared) combination. This choice of wavelengths is dictated by the maximum reflectance of water bodies in the green wavelength spectrum and minimal reflectance in the near infrared spectrum, where vegetation and soil have the highest values. Water reflects virtually no light in the infrared range beyond the visible spectrum, and NDWI effectively leverages this property to detect and monitor the slightest changes in water content (McFeeters, 1996; Xu, 2006; Hernoza et al., 2020; Khajiev, 2021).

In calculating the NDWI, we relied on the intervals provided in Table 2. Higher NDWI values close to +1 indicate high water content or the presence of water surfaces (Table 1). Conversely, lower values, down to –1, suggest signs of drought (Laonamsai et al., 2023) (Fig. 1). The Normalized Difference Water Index (NDWI) was used to identify and distinguish open water or wet surfaces from vegetation and soil backgrounds. NDWI was calculated as (Green – NIR) / (Green + NIR), where reflectance values were derived from Landsat bands (McFeeters, 1996; Xu, 2006). Values close to +1 indicated water saturation, whereas negative values represented drought-prone surfaces. NDWI maps (Fig. 1) were used to determine the extent and persistence of surface water during the spring flooding period and to validate field observations.

Table 2: NDWI intervals for different surface types

NDWI values		Surface type
Low	High	
0.2	1	Water surface
–0.2	0.2	Flooded, wet surfaces
–0.3	–0.2	Moderate drought surfaces, non-water surfaces
–1	–0.3	Drought surfaces, non-water surfaces

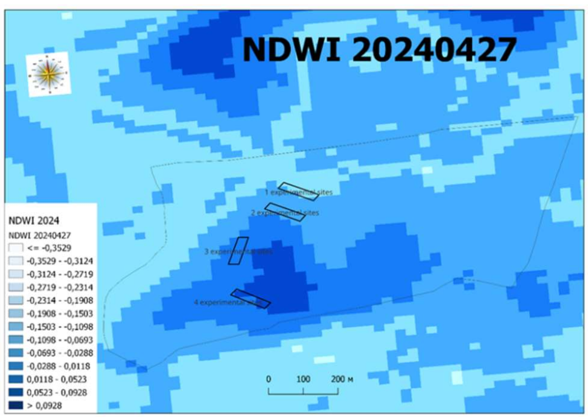

Fig. 1: NDWI map of the studied area as of April 27, 2024.

Flooding maps of the area were created based on the NDWI for the spring period from late April to mid-May (Fig. 2). The analysis of NDVI shows only insignificant differences in the flooded area across the years. The relief of the study area is a concave, irregularly shaped surface. This enabled us to identify specific areas with different flood depths to begin setting up the experiment, as well as areas with different flood volumes — 2500–3000, 3000–3500, 3500–4000, and 4000–4500m^3/ha. NDWI for the 2024 inundation period indicates prolonged wetting of the area and uneven disappearance of water from some parts of the contour. Based on NDWI values for spring 2024, a histogram of the duration of surface flooding at the study sites was created (Fig. 3). This histogram shows the successive release of water from the site and the formation of inundation layers on the experimental plots. The layer with a flood volume of 4,000–4,500m^3/ha remained underwater 3 times longer than the first layer. In this period of time, the layer corresponding to the flood volume of 4,000–4,500m^3/ha was almost constantly flooded up until water removal from the plot. As water was absorbed, the water surface area on the plot decreased. The area of the water surface was calculated by measuring its boundaries. In the 17 days between April 8 and April 25, the water surface area reduced by 228,046.236m^2, and in the 10 days from April 25 to May 10 — by 89,416.087m^2.

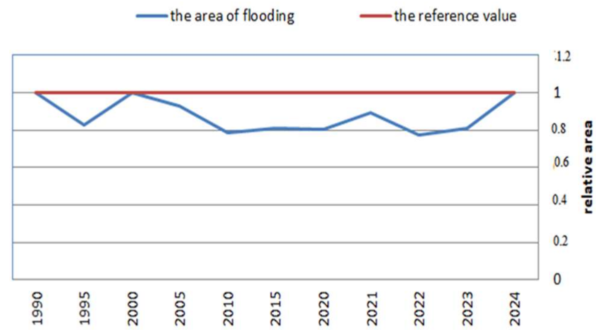

Fig. 2: Extent of relative flooding in the studied area from 1990 to 2024.

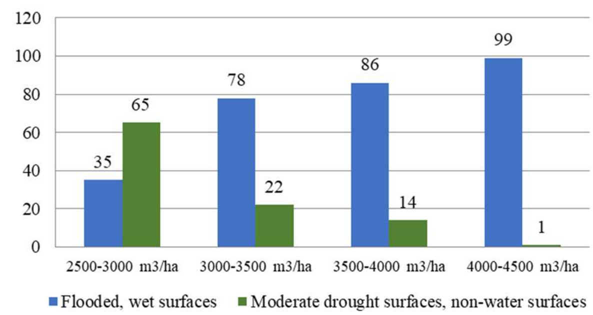

Fig. 3: Duration of surface flooding in experimental areas.

Soil Sample Collection and Chemical Analysis

Soil samples for chemical analysis were collected from each genetic horizon, creating combined samples weighing no less than 1kg. The samples were transferred to labeled cloth bags and transported to the laboratory. Soil humus content was determined by Tiurin's method, which involves oxidizing organic matter by a solution of potassium bromic acid ($K_2Cr_2O_7$) in sulfuric acid (H_2SO_4), followed by quantitative analysis of the amount of recovered chromium following GOST 26213–91. Soil samples were dried in advance to an air-dry state, thoroughly ground, and sieved through a 1mm mesh sieve. Next, a weighed sample (usually 0.1–0.5g) was placed in a flask, and a known volume of $K_2Cr_2O_7$ solution in concentrated H_2SO_4 was added. When exposed to acid and heat, organic matter decomposed and oxidized to CO_2, while hexavalent chromium (Cr^{6+}) reduced to trivalent chromium (Cr^{3+}).

The remaining excess $K_2Cr_2O_7$ was titrated with an iron sulfate ($FeSO_4$) or Mohr's salt (ammonium iron(II) sulfate) solution to quantify the content of organic carbon in the soil. Organic carbon content was determined from the amount of reduced chromium and then converted to humus using a factor of 1.724 (since humus contains an average of 58% carbon). Soil pH was measured in an aqueous extract (1:5 soil to water ratio) using a pH meter. The granulometric composition of the soil was determined by pipette analysis according to the Kaczynski classification. This method is based on separating soil particles by their size through sedimentation in an aqueous medium under gravitational force. The soil sample for analysis was pre-prepared by drying, crushing, and removing organic matter by treatment with a hydrogen peroxide solution. The sample was then dispersed by adding a chemical dispersant solution (e.g., sodium hexametaphosphate) and shaking the sample. The obtained suspension was placed in a graduated cylinder with distilled water. At certain time intervals, corresponding to the sedimentation rate of particles of different sizes, samples of the suspension were taken from specified depths with a pipette. The selected samples were dried and weighed to determine the mass fractions of different particle sizes. Using the obtained data, the content of sand (particle size >0.05mm), silt (0.05–0.001mm), and clay (<0.001mm) fractions was calculated, after which the soil was classified by mechanical composition according to the Kaczynski technique. Organic matter content was determined by oxidation with a potassium bicromic acid solution, measuring trivalent chromium on a photoelectric colorimeter. Cation exchange capacity (CEC) was determined by the CSRIASA method for carbonate soils (organic matter ≤ 6%), involving saturation with Mg^{2+} and subsequent complexometric titration. Exchangeable sodium was extracted with $1.0 mol dm^{-3}$ ($1.0 mol L^{-1}$) ammonium acetate and quantified by flame photometry. Nitrate nitrogen (NO_3^-–N) was measured potentiometrically using an ion-selective electrode with ionic-strength adjustment using alum (aluminum potassium sulfate) or potassium sulfate solutions.

Mobile phosphorus and potassium — using the Machigin method (as modified by CSRIASA) with extraction with ammonium carbonate ($10 g/dm^3$) and further determination of phosphorus using a photoelectric colorimeter and potassium on a flame photometer. Anionic-cationic composition — in an aqueous extract (1:5 soil to water ratio). Anions (CO_3, HCO_3, Cl, SO_4) were determined by titration, argentometry, and turbidimetry; cations (Na, K, Ca, Mg) — by complexometric titration on a flame photometer (Page et al., 1982). Salinity type was determined according to the table developed by Bazilevich and Pankova (1969).

Analysis of Plant Species Composition and Yields

The species composition of vegetation in the flooded area was determined using the method of sample plots with visual identification of plants (Bekmukhamedov & Torekhanov, 2005). The projective coverage and abundance of plants were analyzed using eye estimation and comparison according to the Drude scale (Rumiantsev et al., 2023). Herbarium material was collected, and the flora was processed and analyzed. The Raunkiær classifier was used for bio morphological analysis, and the bio morphological structures of plants were analyzed according to Serebryakov's method. Field studies, yield calculation, and statistical data analysis were conducted according to the methodology of field experiments (Dospekhov, 1985). Plant density was calculated by counting the number of shoots on six $0.25m^2$ plots before mowing. The accumulation of above-ground biomass was measured by mowing grass from four $1m^2$ plots. The conversion to standard 17% moisture content was carried out by drying samples to air-dry mass at 70-75ºC with subsequent conversion.

Correlation Analysis

In this study, we also conducted a correlation analysis to explore relationships between forage grass yields and soil fertility indicators (horizon A), which determine plant growth and development. Plant density and yield data were analyzed using ANOVA under the RCBD design. Post-hoc comparisons between treatments were conducted using Tukey's HSD at $p<0.05$.

RESULTS & DISCUSSION

The studied chestnut soils have a morphological profile structure typical of these soils. The basic agrochemical indicators of the studied soil, depending on flood volume, are given in Table 3. The examined flood volumes did result in some changes in the organic and nutrient content of the soil in the selected layers of the flooded area. In variants with different flood volumes, soil humus content ranged from 2.8 to 3.7% in the uppermost humus horizon. The soil was thus classified as low in humus. In horizon B_1, organic matter content lowered to 1.6–2.7%. Soil nitrogen availability in all variants of the experiment in horizon A was low at 6.3–6.78mg/kg. Phosphorus content was high to very high at 53.2–74.3mg/kg of P_2O_5 but lowered deeper into the analyzed soil profile. Potassium content in the upper soil horizons was characterized as high to very high, ranging from 520.5 to 680.6mg/kg.

Geobotanical analysis of the natural grass stand indicates that the study site is represented by a dominant formation of perennial grasses (*Elytrígia répens*, *Beckmannia eruciformis*) with a total projective coverage of more than 80%. The vegetation of the studied area was mainly represented by the following species: couch grass (*Elytrígia répens*), blackgrass (*Júncus gerárdi*), European slough-grass (*Beckmannia eruciformis*), wand loosestrife (*Lýthrum virgátum*), common wormwood (*Artemísia absínthium*), leafy spurge (*Euphórbia ésula*), curly dock (*Rúmex críspus*), British yellowhead (*Inula britannica* L), common dandelion (*Taráxacum officinále*), Volga fescue (*Festúca valesiáca*), common water-plantain (*Alisma plantago-aquatica*), and sneezewort (*Achilléa ptármica*). Fig. 4 shows the share of each plant and the predominance of couch grass in the studied variants. The application of GIS technologies in this study aligns with recent research trend focused on effective irrigation practices and sustainable water management (Bwambale et al., 2022; Lu et al., 2022). According to the obtained data, humus content in Horizon A ranged within 2.4–3.7% and higher levels were observed with greater flood volumes (Fig. 5).

Interestingly, flooding does not necessarily lead to a decrease in humus levels, but in some cases helps to maintain or even increase them. This is confirmed by the data (Table 3) showing the positive effect of moderate flooding on organic matter content. A similar upward pattern with greater flood volumes is also observed in genetic horizon B. The correlation between humus content and flooding volume is not universal and depends on a certain factors. The increase in humus content observed

Table 3: Key agrochemical parameters of soil in the studied area depending on flooding volume

Genetic horizon (depth, cm)	Humus, %	pH	Cation-exchange capacity mgEq/100g	Exchangeable sodium	Content (mg/kg) NO_3	P_2O_5	K_2O
No flooding							
A (3–18)	2.4	7.68	24.2	0.75	6.3	53.2	635.2
B_1 (18–39)	1.6	7.62	19.33	0.65	5.2	40.3	422.2
B_{Cb} (39–85)	0.4	8.3	13.2	0.38	2.3	15.6	205.4
B_C (85–150)	–	8.8	–	–	–	–	–
Flood volume 2,500–3,000 m^3/ha							
A (3–17)	2.8	7.5	27.3	0.79	6.4	74.3	632.2
B_1 (17–35)	2.24	7.7	25.6	0.75	5.8	52.2	432.3
B_{Cb} (35–100)	0.35	8.2	12.4	0.34	2.5	13.5	321.3
B_C (100–145)	–	8.8	–	–	–	–	–
Flood volume 3,000–3,500 m^3/ha							
A (3–16)	3.4	7.8	26.2	0.86	6.54	61.2	530.2
B_1 (16–30)	2.7	7.9	22.5	0.82	6.2	50.3	490.4
B_{Cb} (30–114)	0.5	8.4	10.6	0.28	2.6	14.8	280.3
B_C (114–152)	–	8.7	–	–	–	–	–
Flood volume 3,500–4,000 m^3/ha							
A (3–20)	3.52	7.5	25.6	0.74	6.39	70.2	520.5
B_1 (20–33)	2.4	7.7	26.8	0.81	6.14	56.4	472.4
B_{Cb} (33–117)	0.45	8.4	8.7	0.24	3.4	13.8	180.2
B_C (117–157)	–	8.8	–	–	–	–	–
Flood volume 4,000–4,500 m^3/ha							
A (3–18)	3.7	7.2	26.7	0.66	6.78	67.8	680.6
B_1 (18–30)	2.6	8.0	24.3	0.69	6.1	48.7	510.4
B_{Cb} (30–122)	0.3	8.4	6.4	0.15	1.84	10.8	212.3
B_C (122–152)	–	8.7	–	–	–	–	–

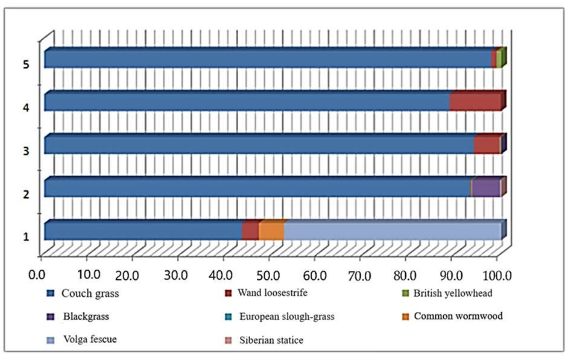

Fig. 4: Share of major plant species in the flooded area depending on flooding volume, %; Variant: 1 — No flooding; 2 — Flood volume 2,500–3,000m^3/ha; 3 — Flood volume 3,000–3,500m^3/ha; 4 — Flood volume 3,500–4,000m^3/ha; 5 — Flood volume 4,000–4,500m^3/ha.

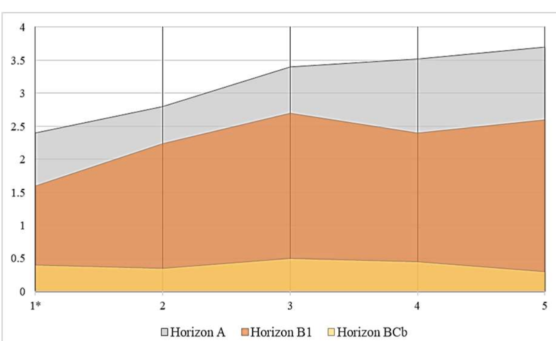

Fig. 5: Soil humus content,%; 1 — No flooding; 2 — Flood volume 2,500–3,000m^3/ha; 3 — Flood volume 3,000–3,500m^3/ha; 4 — Flood volume 3,500–4,000m^3/ha; 5 — Flood volume 4,000–4,500m^3/ha.

with greater volumes could be as a result of anaerobic conditions, increased water availability and soil chemical parameters. This aligns with the studies of Das et al. (2025) and Kenngott et al. (2021), who highlighted that irrigation through flooding mostly increases the abundance of anaerobic taxa, including Firmicutes, Desulfobacterota, methanogens etc. and soil chemical parameters are greatly shaped by flood irrigation. On the contrary, a decrease in humus level or maintenance could be a result of the loss of soluble organic matter through leaching or surface run off or a change in the soil structure as elucidated by Pronko et al. (2021).

Gao et al. (2024) found that flooding increases the content of ammonia nitrogen (NH_4^+–N) and available phosphorus (AP) in the soil, which is associated with anaerobic conditions contributing to the mobilization of these elements (Hadi, 2024).

Nitrate levels in the experimental area ranged 6.3–74.3mg/kg, indicating high biological activity in horizon A (Fig. 6). The primary factors influencing nitrate accumulation are organic matter input, the activity of microorganisms, aeration conditions, leaching, and plant uptake processes. Our results support the conclusions of Di & Cameron (2002), Honeycutt (1999), and Reeves (1997) that nitrates accumulate mainly in the upper soil layers. The results also align with the studies of Tong et al. (2025) who highlighted that in flood irrigation, there is a simultaneous increase of groundwater iron, manganese and nitrogen. Szejgis et al. (2024) slightly disagrees by maintaining the opinion that flooding causes nitrogen loss but the application of prolonged droughts and moderate flooding caused an

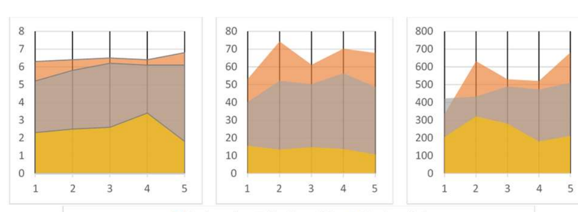

Fig. 6: Soil content of nitrate nitrogen, mobile phosphorus, and mobile potassium,mg/kg; Nitrate nitrogen content Mobile phosphorus content Mobile potassium content; 1 — No flooding; 2 — Flood volume 2,500–3,000m^3/ha; 3 — Flood volume 3,000–3,500m^3/ha; 4 — Flood volume 3,500–4,000m^3/ha; 5 — Flood volume 4,000–4,500m^3/ha.

increase in microbial nitrogen and potassium. On the contrary, the results obtained in this study do not align with multiple studies which highlight the loss of surface nitrogen due to leaching and waterlogging. Kaur et al. (2020) emphasized that soil waterlogging which is consistent with flood irrigation changes soil composition, causes denitrification and nitrogen run off. Increased content of P_2O_5 (53.2–321.3mg/kg) in the upper layers may be connected with the mineralization of organic matter, reduction processes under anaerobic conditions, and sorption on minerals and organic compounds (Kazankapova et al., 2024). Jayarathne et al. (2016) and Maranguit et al. (2017) confirm that flooding can temporarily increase the mobility of phosphorus due to the reduction of iron and manganese oxides. The availability of potassium in the top soil does not translate to available potassium for crop growth due to the fact that flooding may push the potassium beyond the absorption range of the root. Other studies disagree with our results citing that flood irrigation causes leaching and run off of potassium (Rupngam & Messiga, 2024). It is plausible to hypothesize that this increase in top soil potassium is only temporary.

Potassium content (422.2–635.2mg/kg) is at the level characteristic of soils that are not subject to severe salinization. However, flooding can cause a redistribution of potassium in the soil profile. In areas with prolonged flooding, the concentration of K_2O lowers due to leaching, while less intensively flooded areas have higher potassium levels. The results of research conducted in the Okavango Delta (Tsheboeng et al., 2014) confirm that the dynamics of soil potassium content depend on the duration and depth of floods. Overall, the basic parameters of soil show an upward trend with higher irrigation rates, except for mobile potassium, which increases only with a rate of 4,000–4,500m^3/ha, and exchangeable sodium, which rose in the second and third variants. The chemical composition of salts is important for determining soil salinization because it factors in the toxicity of specific salts. The most toxic salt is baking soda, chlorides are less toxic, and sulfates come last. Numerous studies evidence that salt stress, which disturbs the ionic homeostasis of plants, is primarily caused by high concentrations of such ions as Na^+, Cl^-, and SO_4^{2-} in the soil (Hu et al., 2018; Nan, 2022). Soils in the studied flooded area were subjected to sulfate-chloride and chloride salinization (Table 3). The control variant was salinized by chlorides, but the degree of salinization throughout the profile corresponded to non-salinity (0.07–0.095%). Dry residue values in the upper a horizon at the flooded sites ranged from 0.043 to 0.096%. However, plots with different flood volumes varied in the distribution of salts. On the plot with a volume of 2,500–3,000m^3/ha, salinization was weak, and the percentage of dry residue amounted to 0.14% in the 17–35cm soil layer amounted to 0.14%, lowering to 0.131% in the 35–100cm layer. In the other studied variants, the value of dry residue was very low.

This distribution of salts on plots with different flood volumes is typical when salts are washed out from the upper soil horizons to the underlying ones by the gravitational flow of water. Our findings are consistent with a study by Ma et al. (2024), which showed that with the same soil structure, surface irrigation with higher water flow rates resulted in more substantial salt leaching, and lower content of solid dissolved solids in irrigation water made salt leaching more efficient. Overall, flooding with more than 3,000m^3/ha ensured favorable soil salt regimes.

The biomorphological analysis of vegetation demonstrates that the predominant life forms were rhizomatous plants. Specifically, the studied sites were dominated by mesophytes and hygromesophytes, the share of which reached over 60%, while the rest of the plants belonged to xeromesophytes and hygrohelophytes. In all variants of the experiment, the herbage was dominated by couch grass, highly adaptable and resilient in the natural environment (Rasmussen et al., 2014). Considering different flood volumes, the occurrence of couch grass ranged from 269.5 to 374.2units/m^2 in the experimental variants, accounting for 93.2–97.8% of the vegetation, and amounted to 101.8units/m^2 (43.3%) in the control. The wand loosestrife was present in all variants in both iterations of the experiment, reaching maximum concentrations at the irrigation rates of 3,500–4,000m^3/ha (38.3units/m^2 and 11.2%) and 3,000–3,500m^3/ha (20.3units/m^2, 5.7%).

The British yellowhead appeared sporadically at the first and second irrigation rates, although in the last variant, its occurrence increased to 3.4 units/m^2. The Volga fescue accounted for 47.5% of herbage in the control variant while being completely absent in other variants, which probably owes to the plant's intolerance to prolonged flooding. In addition, the control variant had common wormwood in the amount of 13units/m^2. The association between hay yields and flood volume in the two years of the study is illustrated in Fig. 7. In 2023, the highest yield was obtained with the maximum irrigation rate of 4,000–4,500m^3/ha (38.0cwt/ha), or 27.4cwt/ha above the control. With a flood volume of 3,500–4,000 m^3/ha, yields reached 34.0cwt/ha, but the plants in this variant were less valuable as fodder. The variant with the lowest flood volume, 2,500–3,000m^3/ha, outperformed the control by only 3.7cwt/ha. Finally, the variant of 3,000–3,500m^3/ha yielded 13.1cwt/ha higher than the control. Similar results were obtained in experiments by Cavero et al. (2017) and Nassima et al. (2024), where forage alfalfa yields rose linearly with increasing irrigation up to the theoretical crop requirement and above the norm. In 2024, the greatest yields were obtained using the irrigation rates of 3,500–4,000 and 4,000–4,500m^3/ha. These variants demonstrate a reliable increase compared to the control level of 4.8cwt/ha by 11.2 and 11.6cwt/ha, respectively. This result can likely be explained by the predominance of couch grass on these plots, while other plant species could not tolerate prolonged flooding at these rates, as well as by more efficient salt leaching (Ismail, 2000). The irrigation rates of 2,500–3,000 and 3,000–3,500m^3/ha provided 7.6 and 9.3cwt/ha higher yields compared to the control, respectively. On average across the study years, the best yields were observed in the variants of 4,000–4,500m^3/ha (27.2cwt/ha) and 3,500–4,000m^3/ha (25.0cwt/ha), which surpassed control by 253.2 and 224.7%, respectively.

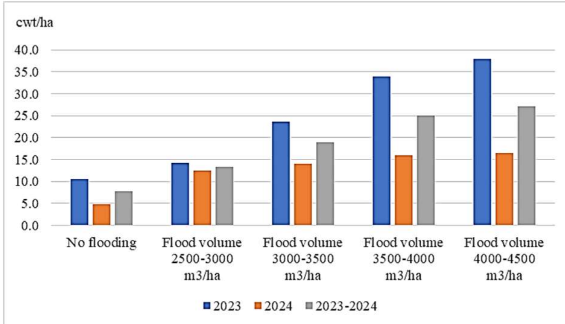

Fig. 7: Hay yields in the flooded area, cwt/ha; 2023 — $LSD_{0.95}$=10.4cwt/ha; 2024 — $LSD_{0.95=}$9.8cwt/ha.

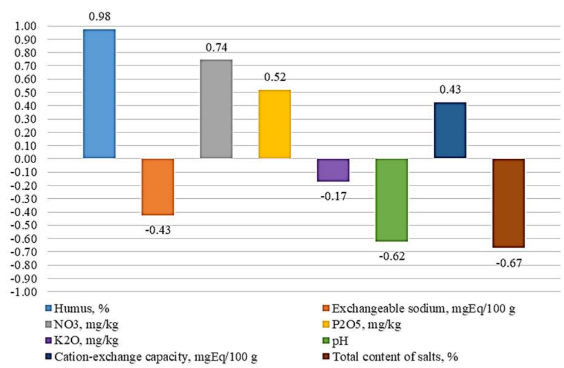

Fig. 8: Correlations between forage grass yields and soil fertility indicators.

Correlation Analysis of Experimental Data

Fig. 8 presents the results of the correlation analysis for yields and soil fertility indicators. The highest correlation is found between yield and humus content in the upper fertile layer (r=0.98). This positive relationship suggests that increased flood volumes resulted in higher yields, which naturally increased soil organic matter (humus) content (Yermagambet et al., 2021). The second strongest correlation is with nitrate nitrogen content (r=0.74), followed by mobile phosphorus (r=0.52), while mobile potassium shows virtually no association with yields. This can be explained by the fact that, in contrast to the high and very high levels of phosphorus and potassium, the content of nitrate nitrogen was low (Table 2). Thus, the plants experienced no shortage of potassium and phosphorus even in the variants with their lowest content, but responded well to higher levels of nitrate nitrogen, producing more biomass (Xie et al., 2015; Plett et al., 2020). An inverse relationship is observed between yields and soil salt content, which is consistent with previous studies (Singh, 2020; Li et al., 2022). In addition to its strong inverse correlation with plant productivity (r=–0.67), the total content of salts has a somewhat weaker inverse correlation with exchangeable sodium (r=–0.43). The examined irrigation rates also affect the pH of aqueous extract, which, in turn, correlates with yields (r=–0.62).

Finally, the parameter of cation-exchange capacity shows a direct moderate correlation with plant yield. Thus, the studied irrigation rates were found to reduce the content of water-soluble salts in the soil, as well as the levels of exchangeable sodium in the soil absorbing complex. This process becomes more pronounced when the irrigation rate is increased beyond 3,000 m^3/ha. The content of basic nutrients also shows an upward trend with greater flood volumes. This study's experimental design's limited temporal scope is one of its limitations. The study, which lasted only two years, falls short in addressing the long-term effects of continuous flood irrigation on plant species succession, soil fertility, and the possible deterioration or resilience of the ecosystem. Such a short timeframe might not account for long-term impacts like the accumulation of toxic elements like sodium, cumulative nutrient depletion, or the salinization of deeper soil layers. Future research on flood irrigation in West Kazakhstan should also consider long-term effects (Ji et al., 2021).

Additionally, the study's use of satellite-derived NDWI to estimate inundation zones is limited by its spatial resolution and might not adequately take into consideration micro-topographic variations that influence local water retention and infiltration dynamics. Even though couch grass is notable, its dominance raises the possibility that biodiversity outcomes are oversimplified, possibly ignoring ecologically significant but subtle changes in secondary species or invasive encroachments. Furthermore, the chemical analyses primarily concentrate on macronutrients and major ions, leaving out toxic trace metals (such as Pb and Cd) and micronutrients (such as Zn, Cu, and Mn), which may become mobile under flooding-induced fluctuating redox conditions. This restricts how thorough the evaluation of soil quality can be. Micronutrients and the impact of flood irrigation on hazardous trace metals should also be the focus of future studies (Karynbayev et al., 2023). From a methodological standpoint, quadrant sampling is common for vegetation surveys, but it might not adequately account for spatial heterogeneity, particularly in areas with patchy flooding. Additionally, the study lacks reliable modeling or predictive simulations to extrapolate findings beyond the immediate region, particularly to areas with different soil textures or climatic patterns (Kenngott et al., 2021). Finally, the research does not integrate socioeconomic parameters such as cost-efficiency, water use sustainability, or farmer adoption potential which are factors essential for translating agronomic success into practical, scalable interventions for semi-arid agriculture. These gaps suggest that while the study is valuable for preliminary insight, further research is required before practical application.

Conclusions

The applied GIS methods allowed us to identify the layers of the flooded area corresponding to the studied flood volumes to achieve the set research objective. In the experimental variants, the main agrochemical parameters increased with higher irrigation rates. The only two exceptions were mobile potassium, which reached its highest value of 680.6mg/kg (horizon A) only with a rate of 4,000–4,500 m^3/ha, and exchangeable sodium, which somewhat increased in the variants of 3,000–3,500 and 3,500–4,000m^3/ha. In general, flood volumes above 2,500–3,000m^3/ha ensured favorable soil salt regimes. The dominant species in the natural herbage was couch grass, whose density reached 269.5–374.2units/m^2 (93.2–97.8% in total vegetation) in the experimental variants and

101.8units/m^2 (43.3%) in the control variant. On average over the study years, the highest yields were obtained in variants with the flood volumes of 4,000–4,500m^3/ha (27.2cwt/ha) and 3,500–4,000m^3/ha (25.0cwt/ha), which surpassed control by 253.2 and 224.7%, respectively. Among soil fertility indicators, the strongest correlation with yields was demonstrated by humus content (r=0.98), nitrate nitrogen (r=0.74), and the total content of salts (r=0.67). Deliberate flooding has a multifaceted influence on soil properties, including anionic and cationic composition, type, and degree of salinization. Consequently, flood management can minimize negative impacts such as secondary salinity and improve the agrochemical properties of soils. However, further monitoring is needed to factor in long-term environmental impacts and to support the sustainable use of soil resources.

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Conflict of Interest: None.

Data Availability: Data will be available at request.

Ethics Statement: All experimental procedures and field studies were conducted in accordance with the ethical standards of the Republic of Kazakhstan and the institutional regulations governing environmental and agricultural research. The research protocol was reviewed and approved by the Bioethics Committee of Zhangir Khan West Kazakhstan Agrarian and Technical University (Approval No. 005, dated February 17, 2025).

Author's Contribution: Conceptualization, writing—review and editing, supervision, project administration, MO and RJ; writing—original draft preparation, methodology, formal analysis, YA and SD; data curation, validation, resources, visualization BN and NU.

Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

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