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Comprehensive monitoring of the meliorative state of irrigated lands as the basis for sustainable water utilization in the Turkistan Region

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Abstract. In the conditions of a growing water scarcity, comprehensive state monitoring of irrigated lands is of particular importance. The study is based on data from the Ministry of Agriculture of the Republic of Kazakhstan and the South Kazakhstan Hydrogeological and Meliorative Expedition. The aim of the work is to assess the current state of the land in the Turkistan Region, analyze the dynamics of groundwater levels and mineralization, and identify the causes of soil degradation. The monitoring covers an area of over 550 thousand ha and includes the systematization of data from laboratory studies and hydrogeological observations. The results of the work substantiate recommendations for the restoration of drainage systems and the optimization of water use. The conclusions formed contribute to the sustainable development of the agrarian sector and the enhancement of the region's food security in the conditions of climate change.

Keywords: meliorative state of lands, irrigated lands, water resources, state monitoring, hydrogeological observations.

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1. Introduction

Modern climate change, growing anthropogenic load, and increasing demand for water resources significantly complicate the tasks of sustainable management of water systems and the ensuring of food security. Of particular importance is the efficient utilization of water resources in regions with arid and sharply continental climatic Conditions, where the sustainability of agricultural Production directly depends on the state of irrigation systems, the groundwater regime, and the meliorative state of lands [1, 2].

Changes in the temperature regime, an increase in the frequency of extreme hydrometeorological events, and the uneven Distribution of atmospheric precipitation have a significant impact on the formation of the water balance of the territories. This leads to the deterioration of water quality, increased groundwater mineralization, intensified soil salinization, and degradation of agricultural land [3, 4]. Under limited freshwater resources, a special role is played by the rational use of surface and groundwater sources, as well as by the improvement of water regulation and conservation systems [5].

The Turkistan Region belongs to regions with a high dependence of agriculture on artificial irrigation. Here, natural Conditions, including a hot climate, an unstable precipitation regime, and significant evaporation, necessitate continuous Control over the state of irrigated lands [6]. Disruption of the water regime, insufficient drainage efficiency and high min-

eralization of irrigation water can lead to secondary salinization, reduced land productivity and deterioration of the ecological state of agrolandscapes [7, 8].

In this regard, comprehensive monitoring of the meliorative state of irrigated lands, including hydrogeological observations, water quality analysis, assessment of soil salinization, and the efficiency of drainage and irrigation systems, is of particular relevance [9, 10]. The obtained data make it possible to identify negative trends, forecast changes in natural and meliorative Conditions, and develop scientifically grounded recommendations for the rational utilization of water and land resources [11].

Particular attention should also be paid to infiltration and colmatation processes, as they directly influence water movement in the soil profile, groundwater recharge, and the overall efficiency of drainage systems [12]. At the same time, the suitability of water for irrigation should be assessed according to established water quality criteria and indicators, including mineralization and other parameters that may affect soil properties and crop productivity [13].

The purpose of this study is to comprehensively assess the natural, hydrological, and water management conditions of irrigated areas in the Turkistan Region, and to analyze the factors affecting their meliorative state. Special Attention is paid to the study of the water and salt regimes of soils, the dynamics of groundwater levels and mineralization, the efficiency of irrigation and drainage systems, and the identification of the causes of agricultural land degradation.

The research results aim to provide practical recommendations to improve the condition of irrigated lands, increase water-use efficiency, and ensure the ecological sustainability of the region's agricultural area.

2. Materials and methods

The methodological research complex is based on the integration of field hydrogeological surveys, precision laboratory analyses, and mathematical modeling methods of filtration processes. The object of the study is the irrigated arrays of the Turkistan Region with a total area of 551.4 thousand ha, characterized by complex natural and meliorative conditions of the arid zone. The study relies on a representative sample of state monitoring data for the 2021-2022 cycle, which enables a high degree of reliability in assessing the correlations between climatic factors and the dynamics of the water-salt balance [14, 15].

The basis for collecting primary data was the baseline state observation network, including 1,396 monitoring wells. The well was designed to intercept the main exploited horizons: mid-Quaternary alluvial-proluvial deposits and deeper Upper Pliocene and Upper Cretaceous aquifer systems. The methodology for field measurements of groundwater levels (GWL) was strictly regulated by the observation schedule. Measurements were carried out three times a Month, totaling 23855 instrumental Settlements during the reporting period.

Hydrogeological electrical level meters (EU type) and steel plummets with anti-corrosion coating, calibrated with an accuracy of up to ± 0.01 m, were used to record the level. Before each measurement cycle, a control check of wellhead tightness and a cleaning of the filter space were carried out to eliminate errors associated with clogging. The depth of GWL occurrence was recorded relative to the wellhead with subsequent Settlement into absolute elevations to construct hydro-isohypse maps.

The analysis of the natural and climatic impact on the meliorative state of lands was carried out using data from 12 meteorological stations of RSE «Kazhydromet». The methodology included the calculation of Selyaninov's hydrothermal coefficient (HTC), which makes it possible to assess the degree of aridity of each specific irrigation array:

$$HTC = \frac{\sum P}{0.1 \sum T} \quad (1)$$

where $\sum P$ is the sum of precipitation for the period with temperatures above $+10^\circ\text{C}$; $\sum T$ is the sum of active temperatures.

The use of this indicator made it possible to differentiate the region's territory into zones of critical (Kyzylkum, Zhetysai) and moderate water deficit. To verify the evapo-

ration data, the Lichev-Lebedev method, adapted to the conditions of Southern Kazakhstan, was applied.

To substantiate the possibility of using groundwater from the Bugunskoye, Suzakskoye, and Michurinskoye Fields as alternative irrigation sources, pumping test data were interpreted. The Settlement of transmissivity (km) and storativity (a) coefficients was performed based on the results of tracking the recovery of the level in wells after the cessation of pumping using the Hantush-Jacob method. For the conditions of confined horizons of Upper Pliocene deposits («Darmina» site), the calculation was made using the formula:

$$S = \frac{0.183Q}{km} \lg \frac{2.25at}{r^2} \quad (3)$$

where S is the drawdown of the level; Q is the well discharge; t is the time from the start of pumping. The obtained parameters (transmissivity up to $2.617 \text{ m}^2/\text{day}$) served as input data for numerical modeling of water intake operations over a final period of 10000 days.

Monitoring of the soil salt regime was conducted on 16 key plots, covering a total area of 20000 ha. Soil sampling was carried out layer-by-layer (0-20, 20-50, 50-100, 100-150, 150-200 cm) using the soil profile and drilling method. In total, 11045 samples processed at SKHME's accredited laboratory were analyzed.

The chemical-analytical block included:

1. Preparation of aqueous extract (1:5). Determination of dry residue and total mineralization by the gravimetric method.

2. Titrimetric analysis. Determination of chloride ion content (Cl^-) by the Argentometric method and sulfate ion (SO_4^{2-}) by barium precipitation.

3. Flame photometry. Determination of sodium (Na^+) and potassium (K^+) cations on PFA-378 type instruments.

4. Toxicity assessment. Settlement of the sum of toxic salts using the Bazilevich-Pankova formula, which made it possible to classify soils by the degree of salinization (from non-saline to takys).

To assess the quality of irrigation waters of the fields, the SAR (Sodium Adsorption Ratio) classification was applied, which was calculated as:

$$SAR = \frac{\text{Na}^+}{\sqrt{0.5(\text{Ca}^{2+} + \text{Mg}^{2+})}} \quad (4)$$

This indicator, together with Stepanov's irrigation coefficient, enabled assessment of the risk of secondary sodicity when using mineralized groundwater (up to $2.5\text{-}3.0 \text{ g/L}$). The technical characteristics of the monitoring network and the scope of the research performed in 2021-2022 are summarized in Table 1.

Table 1. Technical characteristics of the monitoring network and scope of performed research (2021-2022)

Monitoring object	Quantitative indicator	Control method	Observation schedule
Observation wells	1396	Electrical level meters EU-50 plummet	3 times a month (ten-day)
Hydroposts on canals	48	GRM-21 M current meters, GR-31 rods.	Daily during the growing season
Key plots (salt survey)	16 (20000 ha)	Drilling (0-200 cm) core samplers	Before and after the irrigation period
Meteorological stations	12	Automatic complexes (Kazhydromet)	Continuously
Laboratory analyses, water samples (soil, water)	11045 samples	Titrimetry, flame photometry	According to GOST 26423-85

Spatial interpolation of GWL and mineralization data was performed in ArcGIS 10.8 using the Geostatistical Analyst module. The use of the ordinary kriging method enabled the construction of prognostic maps of the meliorative state with minimal standard error. Statistical processing of the entire data array was carried out using Student's t-test to assess the significance of differences between the indicators of 2021 and 2022, as well as regression analysis to identify the relationship between the volume of water supply and the rate of rise of the groundwater table. The hydrogeological parameters of the exploited aquifer systems are presented in Table 2.

Table 2. Hydrogeological parameters of the investigated aquifer systems

Field (site)	Aquifer system	Formation thickness, m	Transmissivity km), m/day	Storativity (a), m ² /day
Bugunskoye (Timursky)	Q _{III-III} Alluvium	40-65	1730-2411	2.6·10 ⁴
Suzak (Northern)	R ₂ -K ₂ Melpogen	80-120	116-2617	1.5·10 ⁵ -2.5·10 ⁶
Michurinskoye	Q _{IV} modern Alluvium	15-30	208-1514	1.8·10 ⁴
Darmina	N ₂ upper Pliocene	50-90	450-890	2.2·10 ⁵

The parameters indicate considerable variability in the filtration properties and storage capacity of the investigated aquifer systems, reflecting differences in their geological and hydrogeological conditions. The identified differences in transmissivity and storativity demonstrate the heterogeneous hydrogeological properties of the investigated aquifers and should be considered when assessing their potential for irrigation water supply.

3. Results and discussion

3.1. Factors affecting the meliorative state

The natural and climatic potential of the Turkistan Region is a decisive factor in the intensity of soil formation processes. The relief of the region, characterized by the transition from the desert plains of Betpak-Dala (in the north) to the high-mountain systems of the Tien Shan (Sayram Peak, 4299 m), creates a complex hydrodynamic situation.

According to weather monitoring data for 2021-2022, the region's climate remains sharply continental, with a pronounced moisture deficit during the growing season. The average July temperature (28.4°C) and extreme maximums up to +45.0°C (at the Kyzylkum station) cause high evaporation rates that significantly exceed precipitation.

Precipitation analysis showed that its distribution is highly uneven, with up to 89% of the annual norm falling in the autumn-winter period. A critically low level of precipitation in August (0.4 mm), combined with anomalous heat and high evaporation, forms the «evaporative» type of soil water regime. Under such conditions, in the absence of adequate drainage, mineralized groundwater is drawn to the surface, contributing to salt accumulation and secondary salinization over an area of 7.4 thousand ha.

At the end of 2022, the total area of the irrigated land in the region was 551.4 thousand ha. A comparative analysis of the land-use structure revealed a critical problem - excessive fragmentation of plots. The presence of 99593 economic entities with an average allotment size of only 4.9 ha creates insurmountable barriers to systemic land reclamation.

The groundwater monitoring results revealed substantial spatial variations in mineralization and chemical composition across the districts of the Turkistan Region, as summarized in Table 3.

Table 3. Characteristics of mineralization and chemical composition of groundwater in the Turkistan Region (max/min indicators for 2022)

№	Districts	Sampling time	Sampling location	Salinity, mg/dm ³	Chemical composition
1	Otyrar	18.09.22	No 58 Temir	57500	SO ₄ ²⁻ Cl Na+K
2	Otyrar	18.09.22	No 31 Otyrar	1000	SO ₄ ²⁻ HCO ₃ Na+K
3	Sauran	01.09.22	No 2007 Ushkayyk	80870	SO ₄ ²⁻ Cl Na+K
4	Sauran	02.09.22	No 415 Ushkayyk	200	SO ₄ ²⁻ HCO ₃ Ca+
5	Shardara	16.09.22	No 6 Kosseit	3940	SO ₄ ²⁻ HCO ₃ Na+K
6	Shardara	16.09.22	No 18 Sutkent	540	SO ₄ ²⁻ HCO ₃ Na+K
7	Kazygurt	30.08.22	No 45 Kyzylkyya	5100	SO ₄ ²⁻ Cl Ca+
8	Kazygurt	31.08.22	No 45 Kakpak	330	SO ₄ ²⁻ HCO ₃ Mg+
9	Saryagash	01.09.22	No 114 Saryagash	7190	SO ₄ ²⁻ HCO ₃ Ca+
10	Saryagash	02.09.22	No 105 Kyzylzhar	170	SO ₄ ²⁻ HCO ₃ Ca+
11	Ordabasy	13.09.22	No 6 Bugen	25000	SO ₄ ²⁻ Cl Na+K
12	Ordabasy	12.09.22	No 170 Tortkol	160	HCO ₃ SO ₄ ²⁻ Mg+
13	Maktaaral	12.09.22	No 42 Nurlybayev	9780	ClSO ₄ ²⁻ Mg+
14	Maktaaral	10.09.22	No 097 Dostyk	830	SO ₄ ²⁻ HCO ₃ Ca+
15	Zhetysai	10.09.22	No. 137 Atameken	9910	ClSO ₄ ²⁻ Na+K
16	Zhetysai	11.09.22	Nos. 226 Kyzysru	850	SO ₄ ²⁻ HCO ₃ Ca+

Small-scale Production in the Sairam and Saryagash districts (1.2-2.0 ha) makes it impossible to introduce modern agricultural technologies and observe crop rotations. This leads to the degradation of on-farm distribution canals and disruption of design irrigation regimes.

Out of the total area of 551.4 thousand ha, only 489.6 thousand ha were actually used. A detailed analysis of the causes of idleness on 61.8 thousand ha (11.2% of the total fund) highlights key destabilizing factors.

Special Attention is deserved by the situation in the Arys region, where 14.863 ha are idle. Here, the highest percentage of land withdrawal due to a combination of salinization and water scarcity has been recorded. At the same time, the Maktaaral and Zhetysai districts demonstrate intensive land use (over 99% involvement), which, against the backdrop of cotton monoculture (40.4-49.5 thousand ha), poses a threat of long-term depletion of land reclamation.

The hydrological network of the region (Syrdarya, Arys, Keles rivers) and reservoirs (Shardara, Bogen) provide a baseline resource for irrigation. However, the high degree of deterioration of the collector-drainage network (CDN), reduces the overall efficiency of water use.

The presence of 3.1 thousand ha of land with a critically high groundwater table indicates low performance of vertical and horizontal drainage. Under the temperature conditions of 2022 (average $T_{year} = 14.2^{\circ}\text{C}$), a groundwater table depth of above 2.5 m is critical. Capillary rise of mineralized solutions in such zones occurs continuously, which is confirmed by salinization data in the Zhetysai massif.

Comparison of the obtained data with the monitoring results of previous years shows that the region is in a state of «hydrological stress». The increase in the area of used land in Zhetysai (from 82917 to 82978 ha) while maintaining irrigation water shortages in other massifs indicates the need to review water use limits. The technological factor is reflected in the fact that 58% of the lands (36 thousand ha) are not used for «various reasons», which in technical terms means the destruction of on-farm networks. This requires not only reclamation, but also civil engineering investments.

Biological land reclamation is also important, as the dominance of cotton (125.8 thousand ha) should be reduced by increasing the share of alfalfa and grain crops. Perennial grasses in the Kazygurt district (11.2 thousand ha of crops) have already proven their effectiveness as natural drainage.

Water sovereignty is another important aspect. Considering the transboundary nature of the Syrdarya River, the development of artesian irrigation from the Bugun and Suzak fields is a strategic task to compensate for precipitation deficits.

3.2. Technical condition of the collector-drainage network (CDN) and its impact on the salt regime

The efficiency of land reclamation in the Turkistan Region is directly limited by the condition of the drainage infrastructure. The total length of the region's CDN is 5941.34 km, but a significant part of the network is in unsatisfactory condition due to long-term operation (over 40-50 years) and violation of maintenance regulations.

As shown in Figures 1 and 2, open thereby raising collectors are subject to intensive siltation and overgrown with macrophytes (reeds). This reduces their hydraulic efficiency, turning drainage canals into «evaporators», which leads to a rise in the groundwater table in adjacent fields.



Figure 1. Mechanical cleaning of an overgrown drainage collector using an excavator



Figure 2. Mechanical cleaning and restoration of a drainage collector

Of the 1655 vertical wells created earlier, a significant number require major rehabilitation. The period from 1990 to 2002, characterized by a lack of unified Control over hydro-reclamation systems, led to the loss of the design discharge operating mode. The implementation of the WURMIP-2 projects and the activities of the Saryagash SUE «Turan Su»

in the Maktaaral, Zhetysai and Shardara districts have allowed for the stabilization of the water-salt balance. However, without transferring all rehabilitated systems (including 3.3 km of ownerless networks) into state ownership, the risk of re-degradation remains high. The mineralization of drainage water significantly exceeds that of irrigation water, ranging from 1.5 to 5.0 g/l. Chlorides and sulfates dominate in the anion composition, while sodium and magnesium dominate in the cation composition.

The observed chemical composition of drainage water indicates a substantial risk of salt redistribution within irrigated areas, particularly under conditions of insufficient drainage and repeated water reuse. Therefore, maintaining the operational capacity of the collector-drainage network is essential for regulating groundwater levels, limiting salt accumulation in the root zone, and preventing further deterioration of the meliorative state of irrigated lands.

Under the low water availability conditions recorded in 2022, the use of drainage water becomes a necessary measure. However, high salinity requires precise hydrometric accounting using current meters (GR-21M) (as shown in Figures 3 and 4) to prevent secondary soil salinization during re-irrigation.



Figure 3. Zhanaaryk drainage collector affected by siltation and vegetation overgrowth, Saryagash district



Figure 4. Water discharge into the Eastern «Kazakhstan» collector, Shardara district

Thus, the deterioration of the collector-drainage network significantly reduces drainage efficiency and contributes to groundwater rise and secondary soil salinization. Restoration and regular maintenance of drainage infrastructure, together with systematic monitoring of drainage-water quantity and mineralization, are therefore essential for maintaining a stable water-salt regime in irrigated lands.

3.3. Water-salt balance as a management tool

Monitoring results indicate that drainage runoff represents an important component of the water balance in the Syrdarya, Keles, Arys, and Bogen river basins. At the same time, its mineralization and chemical composition determine the potential impact of drainage discharges on the quality of receiving surface waters.

The deterioration and insufficient maintenance of drainage systems since the 1990s have contributed to a rise in the groundwater table and subsequent accumulation of salts in the upper soil horizons. These processes have adversely affected the meliorative state of irrigated lands and increased the risk of secondary soil salinization.

Restoring the productive use of the currently unused 61.8 thousand ha requires more than an increase in irrigation water supply. Rehabilitation of collector-drainage infrastructure, regulation of groundwater levels, and systematic control of the water-salt balance are also required to prevent further land degradation.

The discharge of highly mineralized drainage water into river channels can deteriorate downstream water quality, including in the Kyzylorda Region. Therefore, systematic monitoring of drainage runoff and its mineralization is essential for sustainable reclamation management and has both interregional and, within the wider Syrdarya basin, transboundary significance.

4. Conclusions

Monitoring of irrigated lands in the Turkistan Region during 2021-2022 revealed the principal factors affecting their meliorative state and identified priority measures for reducing land degradation and improving water management.

Extremely high summer temperatures, reaching +45.0°C, together with a severe precipitation deficit during the growing season, form an evaporative soil-water regime. Under these conditions, capillary rise of mineralized groundwater promotes salt accumulation in the upper soil horizons and contributes to secondary salinization over an area of approximately 7.4 thousand ha.

Considerable spatial variability in groundwater mineralization was established across the region. The highest value was recorded in the Sauran district, reaching 80,870 mg/dm³. The predominance of sulfate-chloride water types at highly mineralized sites substantially limits the suitability of such groundwater for direct irrigation.

Of the total 551.4 thousand ha of irrigated land, 61.8 thousand ha remain unused. The main limiting factors include irrigation water shortages, affecting approximately 15.3 thousand ha, and the unsatisfactory technical condition of the collector-drainage network.

The total length of the drainage network is 5941.34 km. Siltation, reed overgrowth, and deterioration of open collectors reduce their hydraulic efficiency and contribute to groundwater rise. The effectiveness of the existing system is further limited by the poor technical condition of a considerable proportion of the 1,655 vertical drainage wells, many of which were constructed 40-50 years ago.

Drainage waters are characterized by mineralization of approximately 1.5-5.0 g/L and predominantly sulfate-chloride composition. Their reuse for irrigation therefore requires systematic monitoring and regulation to reduce the risk of secondary soil salinization and deterioration of surface-water quality.

The high fragmentation of agricultural land, with an average farm size of approximately 4.9 ha, complicates the implementation of coordinated reclamation measures, rehabilitation of irrigation infrastructure, and modern water-saving technologies.

Author contributions

Conceptualization: AZI, VMM; Data curation: AZI, NAB; Formal analysis: AZI, VMM, NAB; Funding acquisition: AZI; Investigation: AZI; Methodology: AZI, VMM; Project administration: AZI, VMM; Resources: AZI, VMM; Software: AZI, NAB; Supervision: AZI; Validation: AZI; Visualization: AZI, NAB; Writing – original draft: AZI; Writing – review & editing: VMM, NAB. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Түркістан аймағында суармалы жерлердің мелиоративтік жағдайын кешенді бақылау тұрақты суды пайдаланудың негізі ретінде

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Аңдатпа. Су ресурстарының тапшылығының артуы жағдайында суармалы жерлерді кешенді мемлекеттік бақылау ерекше маңызды. Зерттеу Қазақстан Республикасы Ауыл шаруашылығы министрлігі мен Оңтүстік Қазақстан гидрогеологиялық және мелиоративтік экспедициясының деректеріне негізделген. Жұмыстың мақсаты - Түркістан аймағындағы жерлердің нақты мелиоративтік жағдайын бағалау, жер асты суларының деңгейі мен тұздылығының динамикасын талдау және топырақтың деградациясының себептерін анықтау. Мониторинг 550 000 гектардан астам аумақты қамтиды және зертханалық деректерді және гидрогеологиялық бақылауларды жүйелеуді қамтиды. Зерттеу нәтижелері дренаждық жүйелерді қалпына келтіру және суды пайдалануды оңтайландыру бойынша ұсыныстарды негіздеуге мүмкіндік береді. Зерттеу нәтижелері климаттың өзгеруі жағдайында аймақтағы ауыл шаруашылығы секторының тұрақты дамуына және азық-түлік қауіпсіздігін арттыруға ықпал етеді.

Негізгі сөздер: жерлердің мелиоративтік жағдайы, суармалы жерлер, су ресурстары, мемлекеттік мониторинг, гидрогеологиялық бақылаулар.

Комплексный мониторинг мелиоративного состояния орошаемых земель как основа устойчивого водопользования в Туркестанской области

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Аннотация. В условиях растущего дефицита водных ресурсов особое значение приобретает комплексный государственный мониторинг орошаемых земель. Исследование базируется на данных Министерства сельского хозяйства РК и Южно-Казахстанской гидрогеолого-мелиоративной экспедиции. Целью работы является оценка фактического мелиоративного состояния земель Туркестанской области, анализ динамики уровня и минерализации грунтовых вод, а также выявление причин деградации почв. Мониторинг охватывает площади свыше 550 тыс. га и включает систематизацию данных лабораторных исследований и гидрогеологических наблюдений. Результаты работы позволяют обобщать рекомендации по восстановлению дренажных систем и оптимизации водопользования. Сформированные выводы способствуют устойчивому развитию аграрного сектора и повышению продовольственной безопасности региона в условиях климатических изменений.

Ключевые слова: мелиоративное состояние земель, орошаемые земли, водные ресурсы, государственный мониторинг, гидрогеологические наблюдения.

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