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НАУЧНЫЙ ЖУРНАЛ

ихайлович Ча́плин (28 июля (9 августа) 0 ноября 1931) — русский и советский учёный пециалист в области отопительно- ционной техники.

Дед писательницы Веры Чаплиной[2]. Потомственный дворянин из рода Чаплиных, восходящего[3] ко Льву Чаплину (середина XV века)[4].

В 1883 году окончил Императорское Московское техническое училище (ИМТУ), а в 1898 году получил в училище должность профессора. В 1898—1909 гг. также преподавал в Московском Училище живописи, ваяния и зодчества.

В 1895 году вместе с коллегой по ИМТУ архитектором В. Г. Залесским Чаплин организовал торговый дом «В. Залесский и В. Чаплин». В 1902 году Залесский и Чаплин построили собственный дом на Большой Дмитровке, 16, в котором их семьи имели по отдельному этажу и где располагались помещения их технической конторы[5]. Среди реализованных проектов торгового дома «В. Залесский и В. Чаплин» — системы отопления и вентиляции почти 1500 зданий[6] в десятках городов Российской Империи: Музей изящных искусств имени императора Александра III, Румянцевский музей, Политехнический музей, Аудиторный корпус Московского университета, Императорское Московское техническое училище, Московское училище живописи, ваяния и зодчества, Александровское военное училище, Брестский (Белорусский) вокзал, автозавод А. М. О., Сандуновские бани, гостиница Метрополь, ресторан Эрмитаж, здание страхового общества «Россия», Алексеевская глазная больница, странноприимный дом Шереметева, храм Василия Блаженного, склеп великого князя Сергея Александровича в Чудовом монастыре, Перервинский монастырь, Заиконоспасский монастырь, храм Марфо-Мариинской обители — все в Москве; храм-усыпальница Юсуповых в Архангельском, Петербургская городская детская больница, Путиловский завод, Архангельские городские ряды, Нижегородский городской театр, Киевский коммерческий институт, царский дворец в Ливадии, Иркутский завод «Треугольник», детская больница в Баку, фабрика Столыпина в Пензе, храм Казанской Божией матери в Риге, электрическая ста... в Рязани, Тамбовский пороховой завод, Волжско-Кам... банк в Самаре, Калужское Епархиальное училище, Императорский Харьковский университет и многие другие.

В 1903 году В. М. Чаплин создал перв... водяного отопления с побудительн... Предложенная им ...

165 ЛЕТ СО ДНЯ РОЖДЕНИЯ

9 августа 2026 г.

ЧАПЛИН ВЛАДИМИР МИХАЙЛОВИЧ

1861-1931 гг.

Г. МОСКВА

РУССКИЙ УЧЁНЫЙ, СПЕЦИАЛИСТ В ОБЛАСТИ ОТОПИТЕЛЬНО-ВЕНТИЛЯЦИОННОЙ ТЕХНИКИ

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Strategic sales management of building materials in a highly competitive regional market

Mustafin Artur
Director
E-mail: malish_62@mail.ru

Стратегическое управление продажами строительных материалов в условиях высокой конкуренции на региональном рынке

Мустафин Артур Рафаэлевич
директор
ООО Торговый Дом-Факел
Республика Татарстан, Кукморский район, Село Манзарас

Abstract

The article examines the strategic management of building materials sales in a highly competitive regional market. The relevance of the study is determined by the fact that building materials trading companies operate in an environment characterized by high price sensitivity, seasonal demand, dependence on construction activity, logistics constraints, and continuous pressure from local competitors, federal retail chains, and online sales channels. The aim of this study is to develop a strategic sales management model for building materials based on assortment management, warehouse management, customer segmentation, and performance indicators. The

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methodological framework of the study includes an analysis of scientific literature, conceptual modeling, and the systematization of sales factors. The study identifies the specific features of the regional building materials market, determines the key sales drivers, and proposes a sales management model for a building materials trading company together with a system of performance indicators. The practical significance of the findings lies in the possibility of applying the proposed approach in the activities of regional building materials trading companies serving private customers, contractors, renovation teams, construction companies, and corporate clients.

Аннотация

В статье рассматривается стратегическое управление продажами строительных материалов в условиях высокой конкуренции на региональном рынке. Актуальность рассматриваемой темы исследования определяется тем, что торговые дома строительных материалов функционируют в среде высокой ценовой чувствительности, воздействия на них сезонного спроса, зависимости от строительной активности, логистических ограничений и постоянного давления со стороны локальных конкурентов, федеральных сетей и онлайн-каналов. Цель статьи состоит в разработке модели стратегического управления продажами строительных материалов с опорой на управление ассортиментом, складом, клиентскими сегментами и показателями результативности. Методическая основа исследования включает анализ научной литературы, а также концептуальное моделирование и систематизацию факторов продаж. В результате раскрыты особенности регионального рынка строительных материалов, определены основные факторы стимулирования продаж, предложена модель управления продажами торгового дома и система показателей оценки эффективности. Практическая значимость полученных результатов состоит в возможности применения предложенного подхода в деятельности региональных торговых домов, работающих с частными клиентами, подрядчиками, ремонтными бригадами, строительными организациями и корпоративными заказчиками.

Keywords: building materials, regional market, strategic sales management, trading company, assortment, warehouse, customer segments, competitiveness, sales performance indicators.

Ключевые слова: строительные материалы, региональный рынок, стратегическое управление продажами, торговый дом, ассортимент, склад, клиентские сегменты, конкурентоспособность, показатели продаж.

Introduction

Sales of building materials in regional markets are influenced by the level of construction and renovation activity, seasonality, logistics costs, inventory levels, product assortment, service quality, and the trust of contractors. In a highly competitive environment, a building materials trading company must establish a strategic sales management system aligned with its target market segments.

In the scientific literature, sales strategies are primarily regarded as a factor influencing sales performance through customer segmentation, customer engagement priorities, and the value proposition offered to customers. For example, H. Terho, A. Eggert, A. Haas, and W. Ulaga rightly argue that sales strategy is closely associated with customer orientation and value-based selling; in their view, sales performance depends on the salesperson's ability to communicate the value of the offering to the customer [1]. Accordingly, in the building materials market, customers evaluate product availability, delivery options, the possibility of ordering additional materials, the quality of consultation, delivery terms, and subsequent support throughout the construction project.

Sales management is also influenced by the external environment. In regional markets, this is reflected in seasonal fluctuations, changes in procurement prices, construction project delays, and competition for contractors. Therefore, strategic sales management should incorporate demand forecasting, customer segmentation, inventory management, and a system of performance indicators. Taken together, these considerations define the objective and scope of the present study.

The aim of the study is to develop a strategic sales management model for building materials in a highly competitive regional market.

Research methodology. The study is based on scientific publications addressing strategic sales management, supply chains in the construction industry, assortment management, inventory management, and regional trade management. The research employs the methods of systematization, classification, conceptual modeling, and comparative analysis.

The subject of the study is a building materials trading company operating in a regional market. As a business organization, it procures materials from manufacturers and distributors, stores them in warehouses, develops commercial offers for different customer groups, and sells its products through sales managers, sales offices, telephone channels, its website, online marketplaces, and direct deliveries to construction sites, all of which determine the specific characteristics of its business processes.

Strategic sales management is understood in this study as a system of decisions aimed at selecting target customer segments, developing the product assortment, managing inventory, establishing pricing policies, enhancing service quality, and monitoring sales performance. A central element of this system is the relationship between the assortment matrix and warehouse availability, since listing a product in a commercial offer without having it in stock results in customer attrition. Conversely, when the warehouse is filled with slow-moving inventory, the trading company ties up capital and reduces its ability to respond to current demand. Achieving an optimal balance between these factors determined the focus of the proposed conceptual model.

Results and discussion

The regional building materials market comprises sellers, buyers, suppliers, contractors, and logistics providers involved in construction, renovation, and finishing projects within a specific geographic area. A defining characteristic of this market is the close relationship between demand and local construction activity, as sales volumes depend on residential construction, private housing projects, renovation activities, municipal projects, commercial construction, and seasonal work.

Construction is characterized by project-based work organization and fragmented interactions among participants. A. Dubois and L.-E. Gadde describe the construction industry as a loosely coupled system in which interdependencies are shaped by temporary project-based relationships [2].

For a building materials trading company, this results in demand instability, as a large-scale project may sharply increase demand for materials, while a delivery delay may lead to the loss of a customer.

Considering the above, the typical competitive characteristics of the regional market can be summarized as follows (Figure 1):

1. high customer price sensitivity;
2. similarity of product offerings across competing sellers;
3. dependence on product availability;
4. the impact of delivery costs on the final purchase price;
5. the significant role of personal relationships with contractors;
6. seasonal fluctuations in peak demand;
7. competition from retail chain stores;
8. the growing importance of online ordering and advance inventory availability checks.

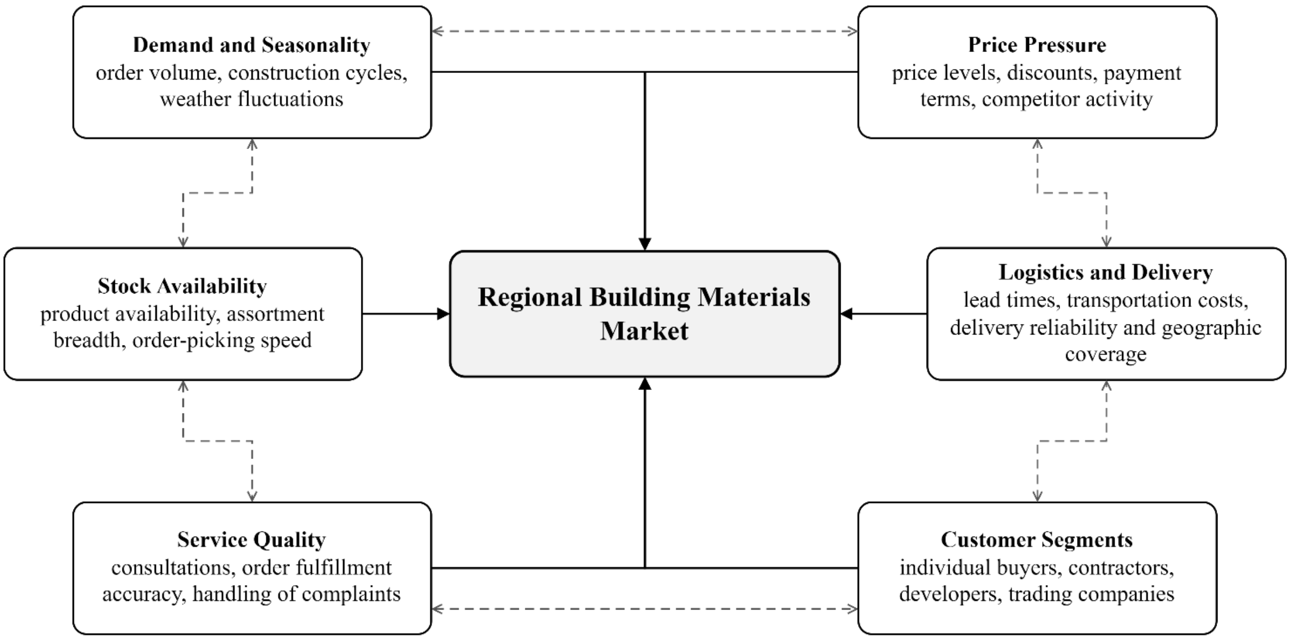

Figure 1. Typical competitive factors in the regional building materials market

The supply chain plays a particularly important role in the operations of a building materials trading company, as it directly affects costs, delivery reliability, and coordination among participants [3]. The sales process is completed only after the product has been handed over to the customer or delivered to the construction site; therefore, warehousing and logistics are integral components of the sales system. This requires monitoring production and shipment schedules, maintaining close communication with suppliers, and planning inventory levels. Sales activities, warehouse operations, and customers' construction projects are closely interconnected; therefore, sales managers must take into account the stage of each project and anticipate future demand.

Recent research confirms that materials management practices influence the performance of construction projects, increasing the importance of inventory availability and supply reliability in sales management [8].

Poor coordination among processes increases the risk of delivery disruptions and customer defection to competitors. This risk can be mitigated through an effective assortment and inventory management system.

Supply-related risks also require regular assessment [9]. In the proposed model, these include supplier reliability, lead times, stock-out risk, and delivery disruptions.

It should be noted that the strategic sales management tools employed by a building materials trading company include the following (Figure 2):

Figure 2. Strategic sales management tools in a building materials trading company

The product assortment forms the foundation of a company's competitive offering [4]. In a building materials trading company, this concept is reflected in both the warehouse and commercial assortment matrices. Accordingly, the assortment should be divided into core, seasonal, project-specific, and made-to-order categories. The core assortment is maintained in stock at all times, the seasonal assortment is expanded in anticipation of expected demand, the project-specific assortment is selected to meet the requirements of individual construction projects, and the made-to-order assortment is used for low-demand items that are not economically justified for permanent inventory.

Warehouse availability is another critical factor, as it determines the actual ability of a trading company to sell a product. Recent research considers assortment, inventory, and pricing as interrelated decisions [5]. Accordingly, inventory levels should be planned based on customer groups, demand frequency, and product profitability.

All these elements formed the basis of the proposed strategic sales management model for building materials (Figure 3):

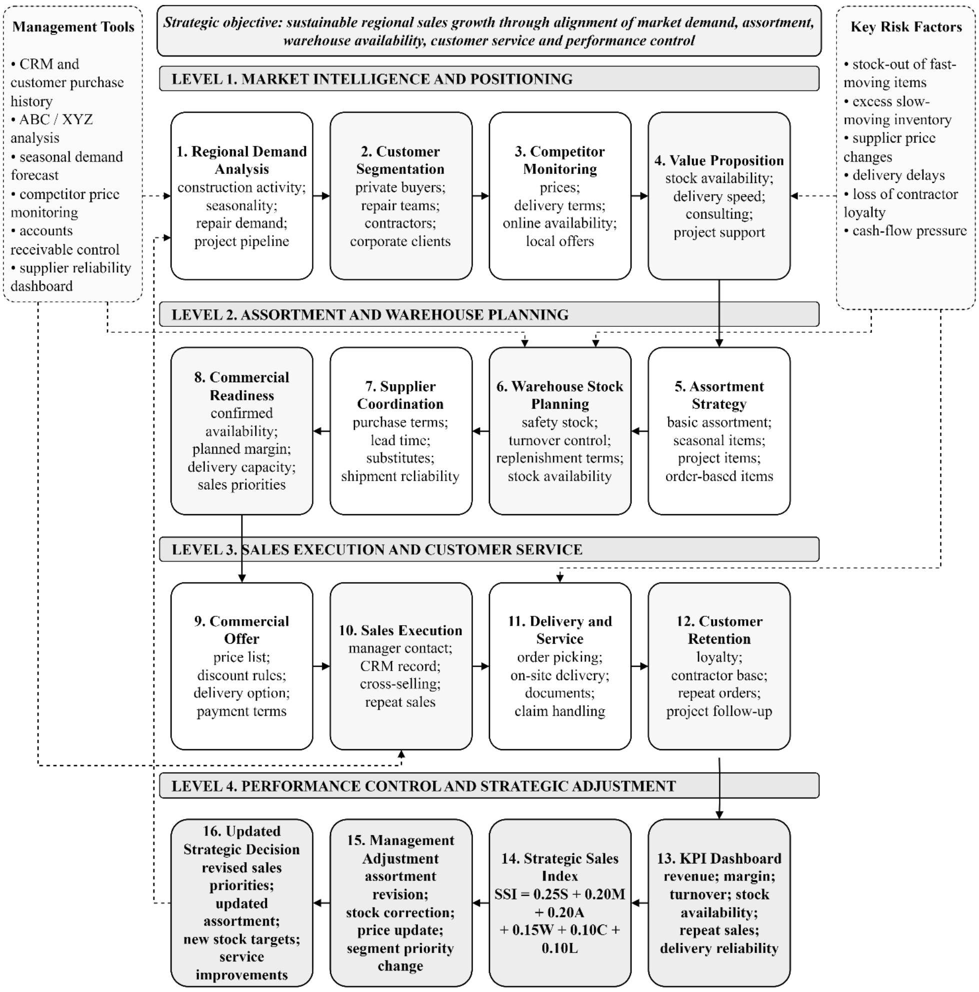

Figure 3. Strategic sales management model for building materials based on assortment and warehouse management

The proposed model is based on the alignment of four interconnected levels, each defining a distinct aspect of strategic sales management for building materials. Within the model, customer segments are classified into private customers, renovation teams, construction contractors, corporate clients, municipal customers, and dealers. Sales parameters are tailored to each segment according to its specific needs and priorities. The effectiveness of sales management should be assessed using several groups of performance indicators (Table 1).

Customer segmentation should also take into account purchase frequency, average order value, repeat purchases, and expected margin contribution [7].

CRM data, demand forecasts, and KPI dashboards improve coordination of sales, inventory, and customer relationships [10, 11]. The described tools support the adjustment of assortment, stock levels, and service parameters.

Table 1.

Performance indicators for evaluating building materials sales in the regional market

Performance indicator group	Indicator	Managerial purpose
Sales	Revenue, profit margin, average order value	Assessment of commercial performance
Customers	Repeat sales, customer retention, active contractors	Assessment of the customer base

Assortment	Inventory turnover, share of high-demand products, slow-moving inventory	Assessment of assortment matrix quality
Warehouse	Product availability, replenishment lead time, inventory accuracy	Assessment of sales readiness
Logistics	Delivery lead time, share of on-time deliveries	Assessment of service quality
Competition	Price index, share of successful customer inquiries	Assessment of competitive position in the regional market

The proposed model can be further enhanced by using an integrated sales performance indicator:

$$SSI = 0.25S + 0.20M + 0.20A + 0.15W + 0.10C + 0.10L,$$

where SSI – Strategic Sales Performance Index;

S – sales plan achievement;

M – profit margin level;

A – assortment quality;

W – warehouse availability;

C – customer retention;

L – logistics performance.

The weighting coefficients reflect the relative importance of the indicator groups in the proposed model. Sales plan achievement receives the highest weight (0.25), followed by profit margin and assortment quality (0.20 each), warehouse availability (0.15), customer retention and logistics performance (0.10 each). The weights are analytically specified and may be empirically calibrated in further studies.

Each indicator is normalized to a scale from 0 to 1, and the resulting index makes it possible to assess both revenue growth and the quality of its achievement.

For example, with $S = 0.88$, $M = 0.76$, $A = 0.82$, $W = 0.90$, $C = 0.78$, and $L = 0.84$, the index is:

$$SSI = 0.25 \times 0.88 + 0.20 \times 0.76 + 0.20 \times 0.82 + 0.15 \times 0.90 + 0.10 \times 0.78 + 0.10 \times 0.84 = 0.833.$$

The resulting SSI equals 0.833, or 83.3 % of the target level; the lowest values are observed for profit margin and customer retention.

Given the critical role of inventory management and logistics in the construction industry, sales performance depends on the warehouse's ability to maintain the availability of high-demand products and on the logistics system's ability to deliver them to customers within the agreed time frame [6].

Conclusion

Strategic sales management of building materials integrates customer relationship management, assortment management, warehouse operations, and supplier coordination. Competitive advantage is determined by responsiveness, accurate identification of customer needs, the availability of high-demand products, and continuous performance monitoring. Sales should be viewed as a manageable system based on customer segmentation, the assortment matrix, warehouse availability, inventory turnover, and repeat sales.

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Effective technologies for strengthening the foundation of low-head hydraulic structures under complex engineering-geological conditions

Nurekeshov Shuxrat Sapargali ugli
PhD student
of the Scientific Research Institute of Irrigation and Water Problems
Republic of Uzbekistan, Tashkent
E-mail: nurekeshovshuxrat@gmail.com

Эффективные технологии укрепления фундамента низконапорных гидротехнических сооружений в сложных инженерно-геологических условиях

Нурекешов Шухрат Сапаргали ўғли
докторант
Научно-исследовательский институт ирригации и водных проблем
Республика Узбекистан, г. Ташкент

Abstract

This article analyzes and evaluates technologies for strengthening small-structure foundations and improving soil properties in challenging conditions. The research aim is to select the most effective and economically viable method for stabilizing weak, multi-layered base layers in the Amudarya River delta, which are characterized by highly deformable, water-saturated dusty sands exhibiting pronounced quicksand properties under dynamic impacts. The methodology involves a comprehensive engineering comparative analysis of current techniques used in hydraulic engineering, including chemical silicatization, microcement grouting, jet grouting, deep foundations, and Deep Soil Mixing (DSM). As a primary result, soil column construction via Deep Soil Mixing (DSM) was selected as the preferred approach. This technology offers high reliability and structural profitability while minimizing geotechnical risks in challenging ground environments. In conclusion, the paper outlines a specialized testing workflow, including laboratory core evaluation and field pilot stabilization, to fully optimize future hydraulic designs.

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Аннотация

В данной статье анализируются и оцениваются технологии укрепления оснований малых сооружений и улучшения свойств грунтов в сложных условиях. Целью исследования является выбор наиболее эффективного и экономически обоснованного метода стабилизации слабых многослойных оснований в дельте реки Амударьи, характеризующейся сильнодеформируемыми, водонасыщенными пылеватыми песками, проявляющими свойства плывуна при динамических воздействиях. Методология включает комплексный сравнительный инженерный анализ современных методов, применяемых в гидротехническом строительстве, таких как химическая силикатизация, цементация, струйная цементация, свайные фундаменты и глубокое смешивание грунтов (DSM). В качестве основного результата устройство грунтоцементных колонн по технологии DSM определено как наиболее предпочтительный подход. Эта технология обеспечивает высокую надежность и рентабельность, минимизируя геотехнические риски в сложных грунтовых условиях. В заключении сформулирован алгоритм проведения опытно-промышленных испытаний и лабораторных тестов кернов для оптимизации проектирования будущих гидротехнических сооружений.

Keywords: small structures, events, technology, foundation, strengthening, soil improvement, safety, deformation, quicksand, Deep Soil Mixing.

Ключевые слова: малые сооружения, мероприятия, технология, основание, укрепление, улучшение свойств грунтов, безопасность, деформация, плывун, Deep Soil Mixing.

Introduction

In recent years, increasing water scarcity has led to greater emphasis on designing, constructing, and rationally using small structures in challenging engineering-geological contexts. According to the Ministry of Water Resources, small structures now outnumber large ones in the republic. Ensuring the long-term safe operation of these small structures is a pressing concern. To meet this challenge, stakeholders should systematically review both positive and negative global experiences in hydraulic engineering and implement best practices accordingly [1,2].

It is essential to recognize factors that inevitably cause the condition of structures to deteriorate, even when used correctly. These include aging materials, weakened foundations, and changes over time in strength, water resistance, and other properties. When needed, engineers must plan for major repairs, reinforcement, or replacement of outdated structures with modern materials.

Soils that quickly lose their properties under the influence of external factors capable of deformation are widespread in the Amudarya River delta. The depth of these soils ranges from several centimeters to tens of meters and even more meters. In such cases, insufficient assessment of the properties of deformable soils leads to the loss of strength and stability of the foundations of small structures, which can subsequently lead to catastrophic consequences. Such cases were very common in the practice of hydraulic construction and caused significant damage to socio-economic sectors [3 – 5]. The reliability of the foundations of small structures and the reduction in the cost of their construction work largely depend on the correct assessment of the properties of the soils in the foundation, the effectiveness of the chosen technological methods and dimensions, and the quality of these works.

Research Objectives: This paper aims to mathematically and logistically analyze geotechnical options to overcome the floating sand layer underneath minor concrete water management channels, identifying a method that maximizes foundation bearing capacity while ensuring project profitability under aggressive aquatic conditions.

Materials and Methods

A complex multi-layered soil layer was identified at the base of the small structure

Layer 1: Sandy loam extending from the surface with a thickness of 3.8 m, characterized by a critically low deformation modulus (E = 5 MPa).

Layer 2: Loamy loam with a thickness of 5.8 m, exhibiting an equally poor load-bearing capacity (E = 4 MPa).

Layer 3: Dusty sands representing a highly critical layer with a thickness of 4.5 m. It lies at a depth of 9.6 m from the surface. This layer exhibits severe floating (quicksand) properties, creating a substantial hurdle for standard engineering setups.

Layer 4: Semi-solid clay with a thickness of 1.0 m. While it behaves as a relatively strong layer, its small thickness does not allow it to be considered a reliable structural load-distribution layer.

The detailed stratigraphic profile and spatial layout of the hydraulic installation are illustrated below (Figure 1).

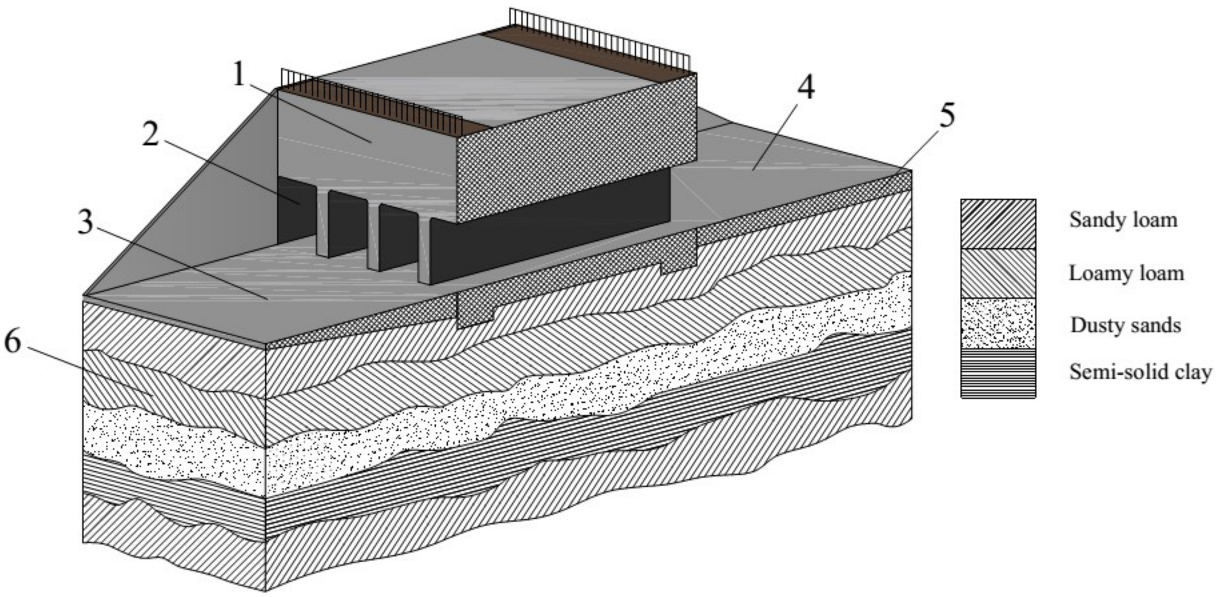

Figure 1. Cross-section of a small structure located in complex soil layers: 1-body of the concrete structure; 2-water passage gap; 3-upper pool; 4-lower pool; 5-structure flutbet; 6-multilayer base

Note on Figure 1: The diagram establishes the geological positioning of the critical quicksand layer (Layer 3) relative to the concrete hydraulic body. It highlights how proximity to hydraulic pool boundaries induces a volatile stress state inside weak subgrades.

The groundwater level is documented in the range of 4.5 – 6.4 m, which directly saturates the soil profile. This indicates that while the upper portion of the third layer (approximately 0 – 1.9 m) lies above the water table, its main body (~ 2.6 – 4.5 m) is deeply submerged, activating acute fluidic behavioral features under dynamic shifts. After construction, constant operational water filling completely saturates all adjacent layers, maximizing quicksand mobility across the system. Compounding this issue, both the soil matrix and groundwater exhibit chemical aggressiveness toward standard concrete compounds, demanding sulfate-resistant cement components and specialized structural barriers [7 – 10].

A quicksand mass consists of water-saturated fine-grained (dusty) sands that shift into a flowing state upon dynamic impact or pit opening. This phenomenon yields:

1. A sharp loss of soil load-bearing capacity.
2. Large and highly uneven settlement patterns across the structure.
3. Rapid flooding and collapse of the excavation pit during early development phases.
4. Severe difficulties in successfully boring piles or embedding foundational units.

Results and Discussion. For the site's unique geotechnical conditions, engineering methods capable of stabilizing the quicksand layer without requiring its physical extraction were systematically evaluated [11,12].

1. Silicatization (Chemical Fixation)

Principle: Pumping chemical mixtures (e.g., sodium silicate «liquid glass» and calcium chloride) through pressure injectors directly into the quicksand matrix. The reaction precipitates a waterproof silicic acid gel that bonds fine sand particles together.

Technology: Well drilling spaced at 0.8 – 1.2 m intervals down to the quicksand base, followed by sequential solution injection to construct a continuous solid block.

Assessment: It offers excellent localized strength, water resistance, and silent, vibration-free execution suited for tight spaces. However, the extreme cost of chemical reagents, uneven solution migration radius, and potential environmental contamination restrict its broad utility. It remains economically justifiable only to avoid massive, risky open earthworks.

2. Cementation (Smolization)

Principle & Technology: Utilizes ultra-fine microcements or synthetic resins capable of passing through the tiny pores of dusty sands. The operational steps mimic silicatization under stringently controlled pressures.

Assessment: Yields phenomenal structural strength and demonstrates good compatibility with surrounding slurry walls or sheet pile frameworks. However, its financial cost is extremely high. Microcements require specialized procurement, and the solution must rely on premium sulfate-resistant compositions to survive the aggressive local groundwater, rendering it the least profitable option for large volumes. It is recommended only for localized reinforcement of critical joints.

3. Jet Grouting

Principle & Technology: A specialized hydraulic cutter on a rotating drill string introduces a cement solution under ultra-high pressure (300 – 600 atm), simultaneously tearing apart the soil matrix and blending it with the binder to create stable clay-cement blocks.

Assessment: Completely replaces weak quicksand with predictable, high-strength soil cement. It allows the construction of seamless underground structural walls and uses sulfate-resistant cement. However, equipment mobilization costs are remarkably high, it demands substantial workspace, and it produces an extensive volume ofground-cement pulp byproduct (slag) requiring disposal. Despite this, it remains technically justified due to its absolute elimination of geotechnical risks.

4. Deep Supports (Bored or Screw Piles)

Principle & Technology: Bypasses the quicksand layer entirely by sinking cast-in-place bored piles or screw piles through the unstable strata until they rest firmly on the deep semi-solid clay layer. Casing pipes prevent soil collapse during concreting.

Assessment: A mature, structurally sound method that effectively relocates structural loads to deeper, stable layers. Screw piles facilitate fast installation with minimal soil vibration. Nevertheless, passing through active quicksand frequently causes casing jams, wellbore wall collapse, or significant drilling fluid loss. Metal screw piles also demand intensive anti-corrosion codings in aggressive waters. Financially, it stands as a highly profitable alternative since establishing a focused pile field is often cheaper than mass soil cementation.

5. Deep Soil Mixing (DSM) Technology

Principle & Technology: Mechanical mixing blades are lowered into the subgrade, mechanically blending the in-situ soil with a customized cement mortar slurry to forge high-density, uniform structural columns.

Assessment: This method ensures superb column homogeneity and structural quality while generating zero construction vibrations or disruptive noise. It supports the direct introduction of sulfate-resistant binding agents. While it demands specialized mixing machinery, its overall economic profitability is moderate and highly competitive compared to Jet Grouting due to superior speed and minimized waste material generation.

6. Full or Partial Soil Replacement

Principle & Technology: Physical excavation of the weak quicksand and layer-by-layer replacement with compacted coarse sand, gravel, or sand-gravel mixtures.

Assessment: Technically unfeasible for this site. Because the quicksand layer occurs at a massive depth of 9.6 m in a water-saturated floodplain environment, keeping the excavation pit stable would require heavy sheet pile barriers and intense continuous pumping. This creates a high risk of trench collapse and undermines adjacent infrastructure due to fine particle migration. Furthermore, disposing of 675 m^3 of saline, muddy soil is highly inefficient and expensive.

Following this analytical review, the evaluated geotechnical methods were synthesized into a standard engineering matrix outlined below (Table 1).

Table 1.

Comparative Engineering Matrix of Geotechnical Methods for Subgrade Stabilization

Technology Category	Evaluated Engineering Methods	Technical Advantages	Main Constraints / Risks
Group 1: Recommended	Deep Soil Mixing (DSM), Jet Grouting	High column homogeneity; minimal waste pulp; completely replaces weak zones.	Demands specialized equipment; high initial mobilization budgets.
Group 2: Conditional	Deep Supports (Bored/Screw Piles)	Effectively relocates loads down to deep stable clay layers.	High risk of casing jams and wall collapse in active quicksand.
Group 3: Not Recom mended	Silicatization, Cementation, Mass Soil Replacement	Silence and vibration-free execution in tight spaces.	Extreme chemical costs; unfeasible trench cave-ins under high water tables.

Conclusions

Based on structural performance metrics, operational logistics, and cost balances, Deep Soil Mixing (DSM) technology is officially selected as the primary methodology for reinforcing the quicksand foundation zone under the small hydraulic structure. To guarantee seamless implementation, the following subsequent technical actions are mandatory:

1. Clarifying Surveys: Execute detailed geotechnical investigations focusing exclusively on the Layer 3 quicksand band to map its exact granulometric distribution and filtration coefficients.

2. Test Strengthening: Install 2–3 pilot soil-cement test columns on-site, away from the core footprint, using the selected DSM gear.

3. Laboratory Verification: Extract core samples from the test columns to evaluate compressive strength and evaluate chemical resistance against local aggressive groundwater parameters. This ensures accurate selection of cement grades and slurry configurations.

4. Final Engineering Design: Utilize empirical data to perform final structural calculations mapping precise column diameters, optimal spatial pitching, immersion depths, and required binder concentrations.

Adopting this systematic approach to Deep Soil Mixing guarantees structural longevity and maximizes project profitability while fully mitigating risks induced by volatile ground environments.

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Laboratory study of filtration regimes in the body of earth dams

Paluanov Daniyar Tanirbergenovich
doctor of Technical Sciences, Professor
of Tashkent State Technical University
Republic of Uzbekistan, Tashkent
ORCID ID: https://orcid.org/0000-0003-2178-8178
E-mail: shuxratnurekeshov7@gmail.com

Saidov Farid Samadovich
Assistent of Tashkent State Technical University, Tashkent State Technical University
Republic of Uzbekistan, Tashkent
ORCID ID: https://orcid.org/0000-0002-1439-8350

Лабораторное исследование фильтрационного режима в теле земляных плотин

Палуанов Данияр Танирбергенович
д-р техн. наук, проф.
Ташкентский государственный технический университет
Республика Узбекистан, г. Ташкент

Саидов Фарид Самадович
ассистент
Ташкентский государственный технический университет
Республика Узбекистан, г. Ташкент

Abstract

The study aims to assess the seepage regime of the earth dam of the Qamashi Reservoir using a 1:100-scale physical model and field observations at section PC16+30. The experiment was conducted in a transparent hydraulic flume using a model constructed from loam soil. The upstream water level was maintained at a constant level corresponding to the elevation of 487.68 m in the prototype. Water penetration into the dam body, the wetting front, and the development of the phreatic surface were observed every 5 minutes. During the experiment, water temperature (19.2 °C) as a control parameter, water density, soil bulk density, settlement of the model crest, and the

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average hydraulic gradient were determined. Seepage water reached the downstream toe 41 hours after the beginning of the experiment. The water density was 999.6 kg/m^3, soil density was 1650 kg/m^3, model crest settlement was 2 mm, and the average hydraulic gradient was 0.12. The phreatic surface formed in the laboratory was close in overall configuration to the field observations. Under the adopted laboratory conditions, the seepage process developed gradually and the average hydraulic gradient did not exceed the specified limiting values. The developed model can be used for a qualitative assessment of the seepage condition of the Qamashi dam; however, the results should be interpreted within the adopted model conditions and structural simplifications.

Аннотация

Целью исследования является оценка фильтрационного режима земляной плотины Камашинского водохранилища с использованием физической модели в масштабе 1:100 и результатов натурных наблюдений на поперечном сечении ПК16+30. Эксперимент проводился в прозрачном гидравлическом лотке с применением модели, изготовленной из суглинистого грунта. Уровень воды в верхнем бьефе поддерживался постоянным и соответствовал отметке 487,68 м в натурных условиях. Проникновение воды в тело плотины, продвижение фронта увлажнения и формирование депрессионной поверхности фиксировались каждые 5 минут. В ходе эксперимента были определены температура воды (19,2 °C) как контрольный параметр, её плотность, объёмная плотность грунта, величина осадки гребня модели, а также средний гидравлический градиент. Фильтрационная вода достигла подошвы низового откоса через 41 час после начала эксперимента. Плотность воды составила 999,6 кг/$м^3$, плотность грунта — 1650 кг/$м^3$, осадка гребня модели — 2 мм, а средний гидравлический градиент — 0,12. Депрессионная поверхность, сформировавшаяся в лабораторных условиях, по своей общей конфигурации была близка к результатам натурных наблюдений. При принятых лабораторных условиях фильтрационный процесс развивался постепенно, а средний гидравлический градиент не превышал установленных предельных значений. Разработанная модель может быть использована для качественной оценки фильтрационного состояния плотины Камашинского водохранилища, однако полученные результаты следует интерпретировать с учётом принятых условий моделирования и допущенных конструктивных упрощений.

Keywords: Qamashi Reservoir, earth dam, seepage regime, physical modeling, phreatic surface, hydraulic gradient, field observations, crest settlement.

Ключевые слова: Камашинское водохранилище, земляная плотина, фильтрационный режим, физическое моделирование, депрессионная поверхность, гидравлический градиент, натурные наблюдения, осадка гребня плотины.

Introduction

Earth dams are among the most widespread structures in hydraulic engineering, and their reliable and safe operation is important for the efficient use of water resources, stable water supply to irrigated lands, and prevention of emergency hydrodynamic events. The technical condition of such structures is determined not only by the strength of the dam body but also by the characteristics of seepage flow through the dam body and its foundation. Uncontrolled seepage can cause migration of soil particles, internal erosion, suffusion, increased pore-water pressure, wetting of the downstream slope, and local deformations [1].

The difference between water levels in the upstream and downstream pools generates seepage flow through the soil pores. As water moves through the dam body, a free seepage surface—the phreatic surface—develops. Its position and the point where it intersects the downstream slope affect the degree of saturation of the dam body, pore-water pressure, seepage discharge, and slope stability. Therefore, determining the position of the phreatic surface is an important part of assessing the technical condition of a dam.

Analytical calculations, numerical modeling, laboratory experiments, and field observations are used to investigate seepage processes in earth dams. Although analytical methods describe the general laws of seepage, they are limited in fully accounting for soil heterogeneity, differences in compaction, and actual boundary conditions. Numerical models can provide high accuracy, but their reliability should be verified against laboratory or field data. Al-Janabi et al. demonstrated close agreement among results obtained using a physical model, the Casagrande method, and the SEEP/W software [2].

The hydraulic conductivity of soils within a dam directly affects the phreatic surface, seepage discharge, and distribution of hydraulic gradients. Mostafa and Zhenzhong found that changes in hydraulic conductivity in dams composed of zones with different seepage coefficients can reduce the overall seepage discharge while increasing pore-water pressure and local hydraulic gradients in some sections [3]. This indicates that seepage safety assessment should consider not only the total seepage discharge but also the phreatic surface and local hydraulic gradients.

Changes in the reservoir level over time also affect the seepage regime. When the water level rises, the saturated portion of the dam body expands and the phreatic surface shifts upward. When the level falls, the seepage field transitions to a new state with a certain delay. Liu et al. showed that the rate of water-level change and the soil water-retention characteristics can cause hysteresis in pore-water pressure and downstream slope stability [4].

Temperature should be recorded as a control parameter in laboratory seepage studies because it affects the dynamic viscosity of water and the hydraulic conductivity of soil. At the same time, temperature monitoring can be used as a diagnostic tool for identifying seepage paths and hidden leakage zones in earth dams. Fabbian et al. demonstrated the possibility of identifying seepage zones through temperature monitoring [5], while Radzicki and Stoliński applied a multi-point thermal-active system under field conditions [6].

Experiments conducted on loess and sand soils have shown that temperature changes can significantly affect hydraulic conductivity. Yang et al. found that the saturated hydraulic conductivity of loess increased with increasing temperature over the range of 7–44 °C [7]. Studies by He, Jiang, and Wang also reported significant changes in the hydraulic conductivity of sand under the influence of temperature [8]. These findings confirm the need to account for water temperature in laboratory experiments.

Studies assessing the seepage condition of earth dams that have been in long-term operation in Uzbekistan have substantiated the need for regular monitoring of piezometric levels, drainage systems, seepage flow, and local deformations [10]. Studies of the Qamashi Reservoir have also considered the possible effects of seasonal temperature changes on water viscosity, the soil seepage coefficient, and water movement [9].

At the same time, there are insufficient studies directly comparing the phreatic surface formed in a laboratory model of low- and medium-height dams constructed from local loam soils with field observations. Existing studies mainly assess seepage processes using analytical or numerical methods, while the interrelationships among flow formation, phreatic-surface development, dam-body settlement, and hydraulic gradients in physical models have received less attention.

The aim of this study is to investigate the development of seepage flow in a 1:100-scale physical model prepared based on the geometric parameters of the Qamashi Reservoir earth dam, determine the position of the phreatic surface, assess model crest settlement and the average hydraulic gradient, and compare the laboratory results with field observations at section PC16+30.

Materials and methods

The seepage processes occurring within the body of the Qamashi Reservoir earth dam were selected as the research object. The main focus was placed on the formation of the phreatic surface, the direction of seepage flow, the hydraulic gradient, and deformations caused by seepage. To compare laboratory results with prototype conditions, winter field-observation data from section PC16+30 of the dam were used. Since a water outlet structure is located at this section, assessing its seepage condition is important from the standpoint of operational safety.

The experiments were carried out in the laboratory of the Department of Hydropower and Hydraulics at Tashkent State Technical University using physical modeling. This method made it possible to directly observe water penetration into the soil body, expansion of the wetting zone, and formation of the phreatic surface under controlled boundary conditions (as illustrated in Figure 1). Previous experimental studies on determining seepage characteristics from pressure, flow velocity, and hydrodynamic parameters were used as a methodological basis for organizing the laboratory observations [13].

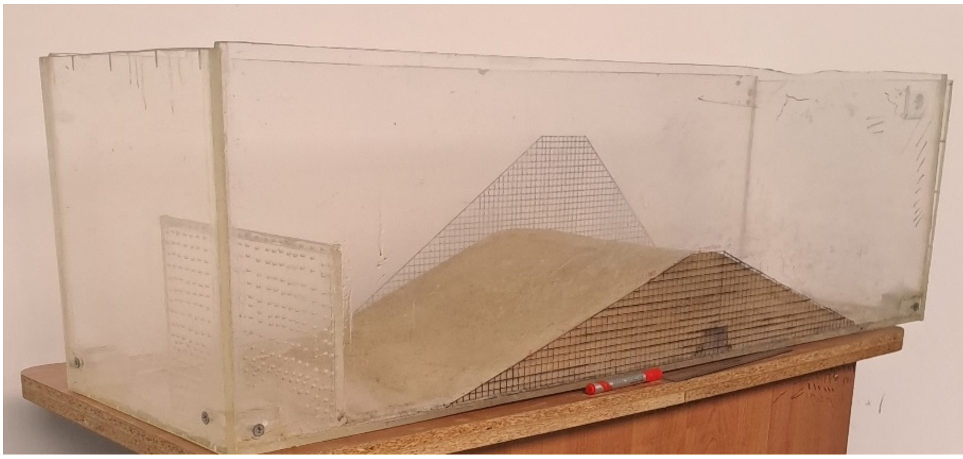

Figure 1. General view of the transparent hydraulic flume and the earth dam model

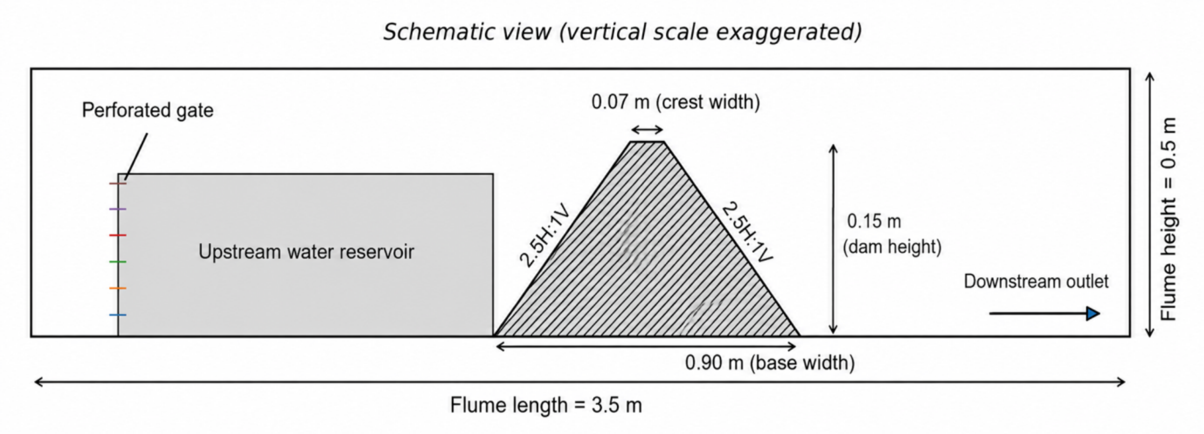

Figure 2. Laboratory setup and schematic geometry of the 1:100-scale earth dam model

The laboratory setup consisted of a transparent plastic hydraulic flume 3.5 m long, 1.0 m wide, and 0.5 m high (Figure 2). The transparent side walls allowed visual observation of seepage flow and the phreatic surface. A 15-cm-high perforated distribution wall was installed upstream to stabilize the water movement. Openings for water discharge were provided downstream to prevent accumulation of seepage water.

A dam model made of loam soil was constructed in the central part of the flume (Figure 2). The model geometry was determined based on the prototype dam parameters: a height of 15 m, a crest width of 7 m, an upstream slope coefficient of $m_1 = 3.0$, and a downstream slope coefficient of $m_2 = 2.5$. Since the linear scale was adopted as 1:100, the model height was $H_m = 0.15$ m, the crest width was $b_m = 0.07$ m, and the calculated base length of the model $L_m = 0.895$ m was practically consistent with the 0.90 m base length adopted in the experiment.

To separately investigate seepage in a homogeneous loam-soil body, some structural elements of the prototype dam were simplified in the experiment. In particular, the downstream drainage system, the concrete lining on the upstream slope, and the water outlet structure in the dam body were not included in the model. Therefore, these simplifications were taken into account when applying the results to the prototype structure.

Geometric similarity between the model and the prototype structure was ensured through the ratio of corresponding linear dimensions:

$$\alpha_l = \frac{l_n}{l_m} = 100 \tag{1}$$

where l_n and l_m are the corresponding linear dimensions of the prototype structure and the model.

Water movement through the dam body was assessed based on soil hydraulic conductivity, the pressure difference, seepage-path length, and hydraulic gradient.

The density of the water used in the experiment was determined using a hydrometer and was 999.6 kg/m³. Water temperature was measured with a thermometer and recorded as 19.2 °C. This temperature was not a comparative indicator of different experimental regimes but a control parameter during the experiment.

The loam soil used for the model was placed in the flume in layers of uniform thickness and compacted evenly until the design shape was obtained. The bulk density of the soil was determined from the ratio of mass to volume and was 1650 kg/m³. Uniform placement and compaction of the layers helped prevent the formation of artificial local high-permeability channels. Previous studies have also substantiated the need to control soil properties to ensure the stability of hydraulic structures [15].

The granulometric composition of the soil was determined at the laboratory of the “Gidroproekt” Joint-Stock Company using sieve-pipette and hydrometric methods. The analysis was performed in accordance with the requirements of GOST 12536–2014 [11]. These results were used to identify the type of model soil and assess its susceptibility to seepage-related deformation.

Before the experiment, the dam model was formed using a 1×1 cm coordinate grid marked on the transparent side wall. The grid made it possible to record the water level, wetting-front position, phreatic-surface points, crest elevation, and profile deformations in a single coordinate system. Water was supplied upstream step by step, and its level was maintained at the model elevation corresponding to the prototype elevation of 487.68 m.

Water penetration into the soil body, expansion of the wetting zone, and movement of the phreatic surface were observed every 5 minutes. Observations continued until seepage water reached the downstream pool and the phreatic surface reached a conditionally stable state. At each stage, the coordinates of the phreatic surface, water levels, seepage outflow condition, and changes in the model profile were recorded. After the experiment, the crest elevation was compared with its initial state to determine vertical settlement. Approaches to the comprehensive assessment of dam settlement and seepage conditions under field conditions have been described in previous studies [14].

The coordinates of the phreatic surface obtained in the laboratory were converted to prototype values using the 1:100 scale and compared with observation data from section PC16+30. The main comparison criteria were the overall shape of the phreatic surfaces, piezometric heads within the dam body, and differences in the area near the downstream pool.

The average hydraulic gradient was determined as the ratio of the difference between piezometric heads in the upstream and downstream pools to the calculated seepage-path length:

$$i = \frac{H_1 - H_2}{L} = \frac{4.68}{38.8} = 0.12 \qquad (2)$$

where H_1 and H_2 are the piezometric heads in the upstream and downstream pools; L is the calculated seepage-path length.

To evaluate the seepage strength and safety of the dam body in accordance with KMK 2.02.02–20 «Foundations of Hydraulic Structures» [12], the calculated hydraulic gradient i must satisfy both the condition based on critical gradient ($i \leq 0.7 i_{cr}$) and the permissible gradient limit ($i \leq i_{\mathrm{perm}} = 0.8$):

$$i \leq min(0.7 i_{cr}\ ,\ i_{\mathrm{perm}}) \qquad (3)$$

During data processing, the phreatic surface, hydraulic gradient, and model crest settlement were analyzed as interrelated parameters.

Results and discussion

During the experiment, the upstream water level was maintained at a constant level corresponding to the Qamashi Reservoir elevation of 487.68 m. Water temperature was 19.2 °C, water density was 999.6 kg/m³, and the bulk density of the model soil was 1650 kg/m³. Seepage flow moved gradually through the dam body and reached the downstream pool after 41 hours. No washing of soil particles, suffusion, or local boiling was observed during the experiment.

The phreatic surface formed in the laboratory (Figure 3) showed a close overall configuration to the winter field observations at section PC16+30. In both cases, the phreatic surface decreased smoothly from the upstream pool toward the downstream pool. This indicates that the physical model qualitatively represented the main features of the seepage process. The importance of comparing physical and numerical model results with field data for assessing model reliability has also been noted in other studies [2, 17].

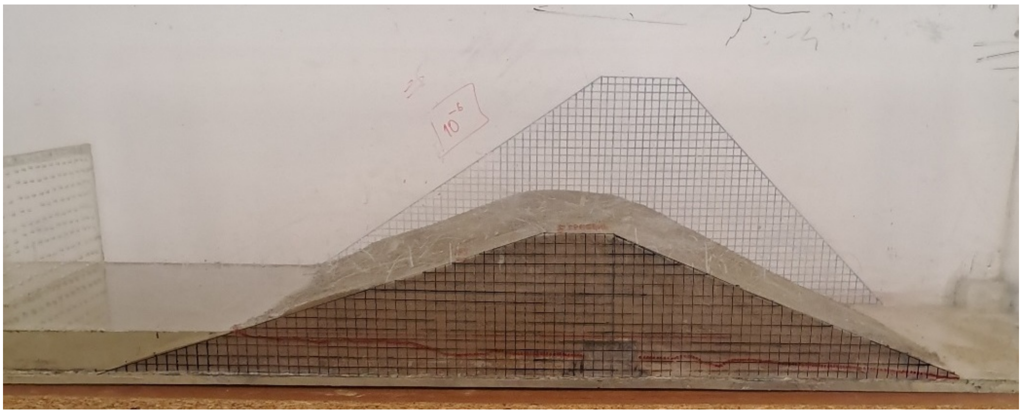

Figure 3. Wetting zone and phreatic surface observed in the laboratory earth dam model

After completion of the experiment, 2 mm of vertical settlement was recorded at the model crest. No abrupt deformation, slope displacement, or distortion of the model profile was observed. However, this value represents only the model deformation under the adopted laboratory conditions and should not be directly equated with settlement of the prototype dam. Previous studies have also substantiated the need for comprehensive monitoring of seepage and deformation processes [13, 14].

With the calculated initial critical gradient $i_{cr} = 0.65$, the condition of seepage strength according to Eq. (3) is expressed as:

$$i = 0.12 \le 0.7 \bullet 0.65 = 0.455 \qquad (and\ \ 0.12 \le i_{\mathrm{perm}} = 0.8) \qquad (4)$$

The relative margin of safety with respect to the critical gradient is $\frac{i}{i_{cr}} = \frac{0.12}{0.65} = 0.18$. This result shows that the average hydraulic gradient did not reach the limiting value under the experimental conditions. At the same time, the average gradient may not fully represent higher values occurring in individual local sections of the dam [3, 16].

The obtained results indicate that the 1:100-scale physical model can be used to study seepage flow and the phreatic surface in the dam body. However, the absence of drainage, concrete lining, and the water outlet structure in the model, as well as the fact that the experiment was conducted at a single water level and temperature, should be considered when interpreting the results. Changes in water level may affect the seepage field and pore-water pressure, as also shown in other studies [4].

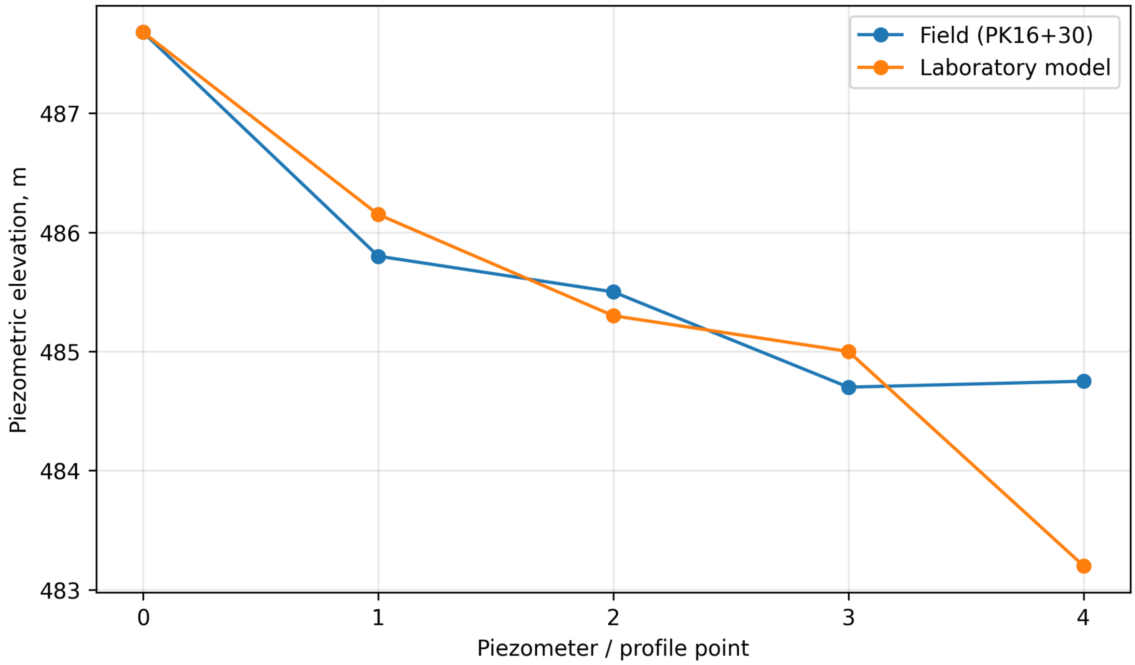

Figure 4. Phreatic profiles under laboratory and field conditions at section PC16+30 (Piezometer elevations measured in meters along the dam section profile)

Figure 4 illustrates the comparative phreatic surface profiles. The horizontal axis represents the control piezometer profile points (from 0 at the upstream side to 4 at the downstream toe), and the vertical axis shows the piezometric head elevations measured in meters (m). As shown in Figure 4, the laboratory model profile closely tracks the field piezometric data points up to point 3, after which the absence of a drainage structure in the model leads to a steeper drop at point 4.

Conclusion

The seepage regime of the Qamashi Reservoir earth dam was investigated using a 1:100-scale physical model. During the experiment, water moved gradually through the dam body, and seepage flow reached the downstream pool after 41 hours. No washing of soil particles, suffusion, or local boiling was observed.

The phreatic surface formed in the laboratory showed a close overall shape to the field observations at section PC16+30. A vertical settlement of 2 mm was recorded at the model crest, while no abrupt deformation or slope displacement was observed. The calculated average hydraulic gradient was $i = 0.12$, which was below the adopted limiting values.

The results show that the physical model can be used for a qualitative assessment of seepage flow and the phreatic surface in the dam body. However, the absence of drainage, concrete lining, and the water outlet structure in the model, as well as the fact that the experiment was conducted under a single water-level and temperature condition, should be taken into account.

For further studies, it is recommended to repeat the experiments under different water levels and temperature conditions, determine local seepage gradients, and compare the results with numerical modeling and expanded field-monitoring data.

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Retrospective analysis of factors affecting pressure pipelines in pumping stations

Rustamov Shoxrux To'lqinboy o'g'li
Head of the Laboratory of the Namangan Regional Center under the Research Institute of Irrigation and Water Problems
Republic of Uzbekistan, Namangan
E-mail: ilyos9595@gmail.com

Kdirbaev Ulugbek Reimbaevich
Doctoral candidate, Research Institute of Irrigation and Water Problems
Republic of Uzbekistan, Tashkent

Axmadaliyev Sardorbek Sobirjon o'g'li
Assistant
Tashkent University of Architecture and Civil Engineering
Republic of Uzbekistan, Tashkent

Ретроспективный анализ факторов, влияющих на давленные трубопроводы насосных станций

Рустамов Шохрух Тулкинбой угли
заведующий лабораторией
Наманганского регионального центра при Научно-исследовательском институте ирригации и водных проблем
Республика Узбекистан, г. Наманган

Кдирбаев Улугбек Реимбаевич
базовый докторант
Научно-исследовательский институт ирригации и водных проблем
Республика Узбекистан, г. Ташкент

Ахмадалиев Сардорбек Собиржон угли
ассистент
Ташкентский архитектурно-строительный университет
Республика Узбекистан, г. Ташкент

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Abstract

The article examines the factors and characteristics affecting pressure pipelines at pumping stations. Retrospective analysis of factors affecting pressure pipelines. During the retrospective analysis of factors affecting pressure pipelines at pumping stations, a pressure test was conducted on the water pipelines. The main technical characteristics and causes of failure of the closed irrigation system, as well as biological corrosion of metal pipes and concrete structures of pumping stations, were analyzed. Methods for diagnosing the technical condition of pipelines, namely X-ray, ultrasound, and acoustic emission and thermal imaging, were proposed, and the results were analyzed. To improve pipeline efficiency, we extend the service life of pipelines by performing hydrodynamic cleaning under high pressure, operating outgoing robots, cleaning with chain devices via brush feed or brush feed, and applying coatings to water pipelines during repair, specifically using an epoxy mixture. In addition, painting them with various varnishes and paints also helps to increase the service life of the pipes. Furthermore, it will be possible to achieve more efficient use of the pumping station without observing the cavitation process occurring in the pumps.

Аннотация

В статье рассматриваются факторы и характеристики, влияющие на напорные трубопроводы на насосных станциях. Ретроспективный анализ факторов, влияющих на напорные трубопроводы. При ретроспективном анализе факторов, влияющих на напорные трубопроводы насосных станций, были проведены испытания давления в водопроводных трубопроводах. Проанализированы основные технические характеристики и причины отказов закрытой оросительной системы, а также биологическая коррозия металлических труб и бетонных конструкций насосных станций. Предложены методы диагностики технического состояния трубопроводов, т.е. рентгеновские, ультразвуковые и акустические методы эмиссии и контроля, и проанализированы результаты. С целью повышения эффективности трубопроводов гидродинамическая очистка под высоким давлением, запуск выходящих роботов, очистка цепными устройствами с помощью щеточной подачи или щеточной подачи, нанесение покрытия на водопроводные трубы при их ремонте, то есть использование эпоксидной смеси, продлевает срок службы труб. Кроме того, их окраска различными лаками и красками также способствует увеличению срока службы труб. Также создается возможность достижения более эффективного использования насосной станции без наблюдения процесса кавитации, происходящего в насосах.

Keywords: Pump, retrospective, closed irrigation, pipeline, diagnostics, hydrodynamic cleaning, pressure, epoxy mixture.

Ключевые слова: Насос, ретроспективный, закрытый полив, трубопровод, диагностика, гидродинамическая очистка, давление, эпоксидная смесь.

Introduction

The large number of failures of land reclamation pipelines in the closed network and the unevenness of their distribution during the irrigation period are associated with severe operating conditions: seasonality and interruptions, periodic full or partial discharge, uneven water supply, significant changes in total and individual water consumption caused by frequent switching on and off sprinkler equipment, and the inability to quickly redistribute pressure and flow velocity. All of this negatively affects the occurrence of dynamic loads, the strength of the pipelines, the tightness of the pipeline walls, and, consequently, the reliability of the network.[2]

The lack of internal insulation in steel water pipes and the continuous contact of the metal with the corrosive environment allow for the development of almost all types of corrosion.[8]

A distinctive feature of corrosion processes is their complexity and multi-stage nature. Usually, the corrosion process consists of at least three main stages: transferring the reactants to the phase interface—the reaction zone; essentially, a heterogeneous reaction; and removing reaction products from the reaction zone (Fig. 1.1).[4]

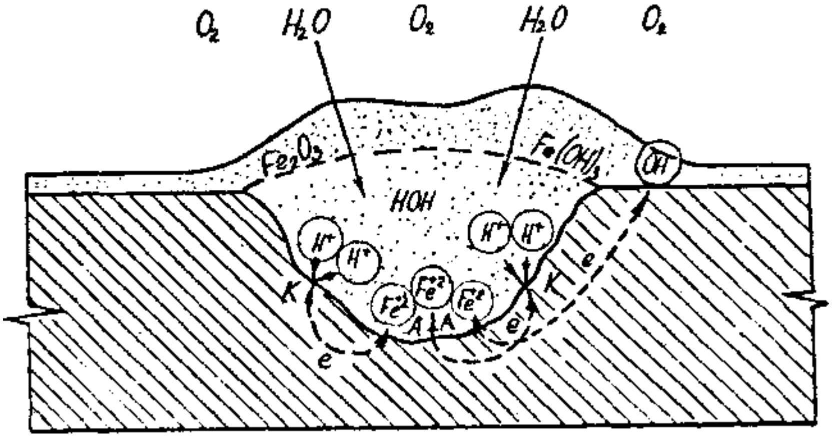

Figure 1.1. Diagram of the intra-ulcer corrosion process

K – cathode sites for reducing oxygen or hydrogen;

A – anodic sites for iron reduction.

Iron corrosion in a neutral aqueous medium occurs with oxygen depolarization. In this case, the cathodic process is the process of ionization of oxygen by the reaction[4]:

O_2 + 4e+2H_2O = 4OH, (1.1)

and anodic – the process of ionizing iron by reaction:

Fe + 2H_2O = Fe^{2+} 2H_2O + 2e (1.2)

During operation, corrosion products, together with particles of mineral origin, form deposits of various shapes and densities on the walls, which leads to a deterioration in the hydrodynamic properties of the pipes, an increase in energy costs for water transport, and water loss due to corrosion.

The results of physical examinations and laboratory analyses have been reviewed, proving the biocorrosive wear and tear of pressure pipelines and reinforced concrete structures of pumping stations. A study of the movement of fine particles showed that the components of the water flow do not contain abrasive materials, as sand materials with a diameter of more than 0.01 mm settle in the pump station's advance chamber. Therefore, complete wear of the entire internal surface of the steel pipeline is not observed.

Materials and methods

Diagnosing the technical condition of existing pipelines is one of the most important indicators affecting their operation. The degree of wear and tear of water pipelines is determined by the reliability indicators of their operation. To ensure the safety and efficient operation of piping systems, the piping system must be inspected regularly.[1]

The choice of the method for repairing an existing pipeline is based on an analysis of the technical and economic indicators of its technical condition. The determining factor, in this case, should be the presence of continuity of the pipeline walls in the test zone and the number of their disruptions.

Diagnosing the condition of the pipeline is a vital component of ensuring the safety and efficient operation of the system. This makes it possible to identify problems at an early stage, prevent accidents and pipe cracks, and extend the service life of the pipes. Various diagnostic methods, such as X-ray, ultrasound, pressure testing, and the use of acoustic emission technology, provide rapid and accurate information about the condition of the pipes. Regular cleaning and inspection of pipes will help reduce economic losses, plan repairs, and meet regulatory requirements.[7],[9]

Currently, the most common methods for diagnosing pipelines are as follows[5]:

The X-ray method: in which X-rays are passed through tubes and an image is recorded on film or a sensor to detect defects. A uniform background illumination on the developed film indicates the absence of defects. If a leak is detected, it is a thickening of the weld or a drop of metal (weld joint). If a blackening is detected, it is a defect, i.e., a hole.

Ultrasound and acoustic emission methods: Mechanical ultrasonic oscillations are sent to the metal pipe using a transducer in a direction specified by the operator and observed on a defect detector. The ultrasound hits the defect surface, is reflected, and returns to the transducer.

Tele-inspection method: The tele-inspection method developed by TARIS NPO consists of moving a robot equipped with a video camera along the pipeline being diagnosed and transmitting the video image to a computer display.

Results and discussion

Pressure testing: a method that evaluates the strength and tightness of pipes by applying increased pressure to the system. There are two main types of pressure tests[3]:

• Hydrostatic testing: This method involves filling a pipeline with water or another liquid and then applying a specified pressure. By monitoring pressure fluctuations and searching for fugitives, you can determine the presence of damage in the system. This method is typically used during the construction stage or after pipe repairs.

• Pneumatic test: In this case, the pipeline is filled with air or gas, and the pressure is raised to a certain level. Then, a leakage test is performed using specialized equipment to detect pressure changes.

Advantages of pipe diagnostics[1]:

• Increased safety: regular inspection of underground pipelines helps prevent accidents and displacements, which helps ensure the safety of personnel and the environment.

• Reducing economic losses: Identifying problems at an early stage allows for measures to be taken to eliminate them before they lead to serious disruptions or accidents. This helps reduce economic losses associated with equipment downtime or system shutdowns.

• Extending the service life of pipes: regular diagnostics allow for the detection and elimination of damage, wear, and corrosion at early stages, which helps extend the service life of pipes. Regular maintenance and repair help maintain their efficiency and reliability over the long term[6].

Mechanical pipe cleaning

• Cleaning with brushes – effective for removing debris and other small pollutants.

• Rubber mats – Do not damage the pipe surface during the process of removing large obstacles, as well as during cleaning.

Restoration and repair of pressure pipelines

To eliminate minor problems occurring inside the pressure pipelines, restoration work is carried out using the following methods (Fig. 1.2).

1. hydrodynamic high-pressure cleaning;
2. running outgoing robots;
3. by brush feed;
4. cleaning by chain devices or brush feed.

Figure 1.2. Pipeline cleaning equipment with brush or chain drives

The selection of technologies or methods for pipe repair is initially carried out based on the general or specific situations of the problems observed in them.

Coating (cement or paint). Manual repair.

When repairing water pipelines, it is possible to apply a coating to them, but it is necessary to take special measures against negative changes in water quality. The use of cement in the coating method is considered obsolete, and in Germany and the UK, an epoxy mixture is currently used instead of this material. In addition, painting them with various varnishes and paints also helps to increase the service life of the pipes.

Conclusion

The pressure pipelines of pumping stations are one of the most important and responsible parts of hydraulic structures, and their reliable and safe operation largely depends on a comprehensive study and assessment of the factors influencing the operation process. The conducted retrospective analysis shows that the service life, durability, and occurrence of emergency situations in pressure pipelines are directly linked to a complex of interconnected natural, technical, and technological factors.

In general, a retrospective analysis of the operating conditions of pressure pipelines over the past period allows for the development of scientifically grounded preventive measures and a new diagnostic system to prevent future accidents, increase the reliability of pumping stations, and improve their energy efficiency.

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Assessment of spatial and environmental deficits in Tashkent residential development by morphological type

Shoumarova Oydin
PhD Candidate
Department of Design, Tashkent University of Architecture and Civil Engineering
Republic of Uzbekistan, Tashkent
E-mail: ayupovaoydin@gmail.com

Оценка пространственно-средовых дефицитов жилой застройки Ташкента с учётом морфологических типов

Шоумарова Ойдин Аббос қизи
докторант кафедра
Дизайн, Ташкентский архитектурно-строительный университет
Республика Узбекистан, г. Ташкент

Abstract

The study assesses spatial and environmental stress across morphological types of Tashkent's residential fabric. The analysis was conducted in QGIS using 983 territorial units and combines morphometric indicators, street-network parameters, and recreational accessibility. Morphometric deficit was defined relative to FSI, GSI, and OSR distributions within each morphotype. Network deficit was assessed through node and intersection density, while recreational deficit was measured by network distance to the nearest recreational space. The diagnostic variables were integrated into a five-level stress scale. High or critical stress was identified in 48.0 % of the analysed territories. The highest shares occurred in transformed mahalla development M1b (74.8 %) and traditional M1a (64.8 %), while the lowest were recorded for microdistrict types M2a (16.8 %) and M2b (14.3 %). The results show that stress is not linearly determined by density but depends on morphology, connectivity, and recreational accessibility. The approach can identify areas where further densification requires restrictions or compensatory planning measures, providing a practical basis for differentiated regulation of residential development according to its initial morphological structure.

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Аннотация

Цель исследования — выявить различия в пространственно-средовой напряжённости основных морфологических типов жилой ткани Ташкента на основе комплексной пространственной диагностики. Исследование выполнено в QGIS на выборке из 983 территориальных единиц и объединяет морфометрические характеристики, параметры улично-пешеходной сети и рекреационную доступность. Морфометрический дефицит определялся относительно распределения FSI, GSI и OSR внутри каждого морфотипа. Сетевой дефицит оценивался по плотности узлов и пересечений, а рекреационный — по сетевому расстоянию до ближайшего рекреационного пространства. Диагностические признаки объединены в пятиуровневую шкалу пространственно-средовой напряжённости. Высокий или критический уровень выявлен для 48,0 % исследованных территорий. Наибольшая доля таких территорий установлена для трансформированной махаллинской застройки M1b — 74,8 % и традиционной M1a — 64,8 %, а наименьшая — для микрорайонных типов M2a и M2b: 16,8 и 14,3 % соответственно. Результаты показывают, что напряжённость не определяется плотностью линейно, а формируется сочетанием морфологии, связности и рекреационной доступности. Предложенный подход может применяться для предварительного выявления территорий, где дальнейшее уплотнение требует ограничений или компенсирующих планировочных мер при градостроительном регулировании жилой застройки.

Keywords: Tashkent, residential development, densification, urban morphology, morphotype, spatial and environmental deficits, recreational accessibility.

Ключевые слова: Ташкент, жилая застройка, уплотнение, городская морфология, морфотип, пространственно-средовые дефициты, рекреационная доступность.

Introduction

Residential densification affects not only development intensity but also the organization of open spaces, pedestrian connectivity, and access to recreational areas. Similar density values may correspond to substantially different spatial conditions; therefore, density alone is insufficient to characterize the environmental performance of residential areas. This issue is particularly relevant to Tashkent, where traditional mahalla fabric, Soviet microdistricts, and contemporary mid- and high-rise residential developments coexist. Their contrasting spatial structures respond differently to densification.

The Spacematrix approach developed by M. Berghauser Pont and P. Haupt treats density as a multidimensional characteristic of urban form [1]. A. Dragutinovic, W. Quist, and U. Pottgiesser emphasize the role of open-space morphology in residential environments [2], while S. Ibrahim et al. demonstrate links between urban morphology, street-network configuration, and walkability [3]. These findings support an integrated assessment combining morphometric characteristics, spatial connectivity, and recreational accessibility.

A previous analysis of Tashkent's residential fabric [4] identified six main morphotypes: M1a — traditional mahalla development; M1b — transformed mahalla development; M2a — classic Soviet microdistrict; M2b — transformed microdistrict; M3 — compact mid-rise development; and M4 — high-rise intensive development.

The aim of this study is to identify differences in spatial and environmental stress among the main residential morphotypes of Tashkent through an integrated assessment of morphometric, network, and recreational characteristics.

Materials and Methods

The study was conducted in QGIS using a geospatial database of Tashkent residential areas, including residential boundaries, buildings, the street and pedestrian network, and recreational spaces. After data preparation and filtering, the final sample comprised 983 territorial units.

Residential areas were classified into six morphotypes: M1a — traditional mahalla development; M1b — transformed mahalla development; M2a — classic Soviet microdistrict; M2b — transformed microdistrict; M3 — compact mid-rise development; and M4 — high-rise intensive development. Their characteristic spatial patterns are shown in Figure 1. Of the 983 units, 965 were assigned to these six stable morphotypes, while 17 were classified as mixed and one as transitional.

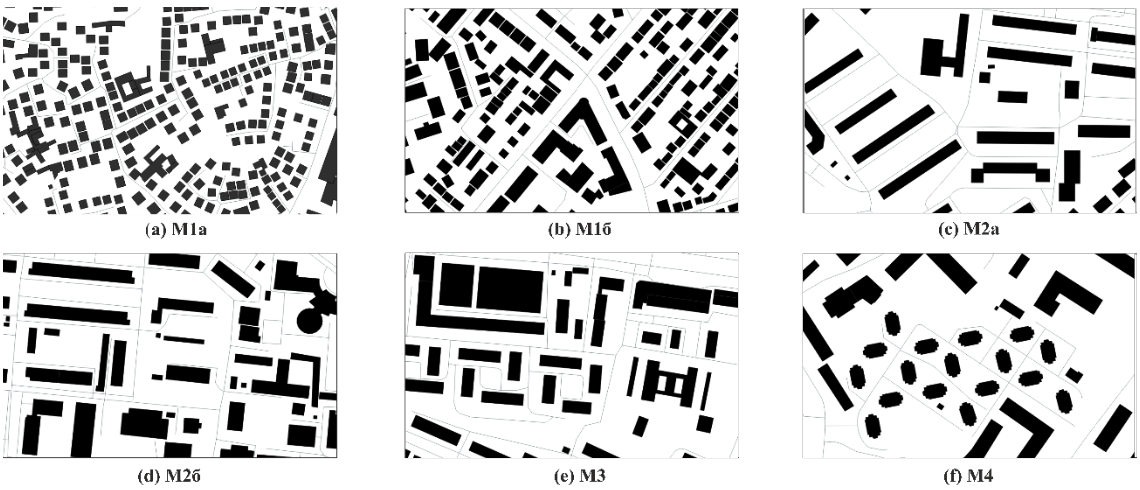

Figure 1. Main residential morphotypes of Tashkent: (a) M1a; (b) M1b; (c) M2a; (d) M2b; (e) M3; (f) M4

The integrated assessment included three components: morphometric, network, and recreational. The morphometric component used the Spacematrix indicators FSI, GSI, and OSR [1], previously applied to residential development in Tashkent [1, 4].

To account for differences between morphotypes, morphometric deficits were defined relative to the indicator distribution within each type rather than by a single citywide threshold. FSI or GSI values above the third quartile (q3) were considered high, while OSR values below the first quartile (q1) were considered low. A morphometric deficit was recorded when high FSI or GSI coincided with low OSR. The resulting thresholds are presented in Table 1.

Table 1.

Morphometric deficit thresholds by morphotype

Morphotype	FSI (q_3)	GSI (q_3)	OSR (q_1)
M1a	0.662	0.256	1.129

Morphotype	FSI (q_3)	GSI (q_3)	OSR (q_1)
M1b	1.1495	0.3785	0.5015
M2a	0.982	0.226	0.7875
M2b	1.2815	0.280	0.582
M3	1.779	0.309	0.393
M4	3.287	0.377	0.1935

The network component characterized permeability through the density of street and pedestrian network nodes and intersections [5]. The lowest class was defined using the Jenks natural breaks method [6]; values below 2 nodes/ha were treated as an internal diagnostic threshold for network deficit.

The recreational component measured network distance from the centroid of each territorial unit to the nearest recreational space. Three categories were used: ≤500 m — no deficit; 500–1000 m — moderate deficit; >1000 m — pronounced deficit [7, 8]. The diagnostic variables were combined into an integrated stress index:

T=morph_def+net_def+rec_def, where morph_def and net_def take values of 0 or 1, and rec_def takes values of 0, 1, or 2 according to recreational accessibility.

The index defined five stress levels from 0 (balanced) to 4 (critical), which were subsequently compared across morphotypes.

Results and Discussion

The integrated assessment revealed substantial spatial variation across Tashkent (Figure 2). Of the 983 territorial units, 48.0 % were classified as having high or critical spatial and environmental stress.

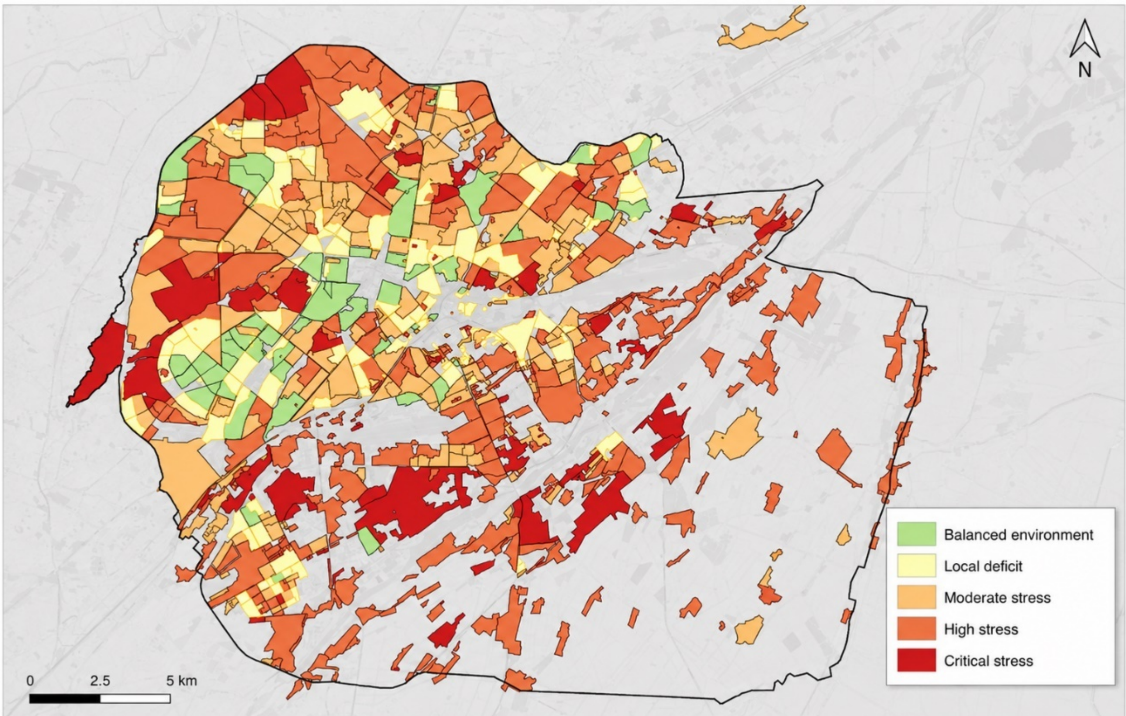

Figure 2. Spatial and environmental stress in residential areas of Tashkent

Comparison with the morphological typology revealed substantial differences between residential forms. The analysis covered 965 units assigned to the six stable morphotypes.

Table 2.

High and critical spatial and environmental stress by morphotype

Morphotype	Total units	High	Critical	High + critical, %
M1a	438	220	64	64.8
M1b	139	77	27	74.8
M2a	184	26	5	16.8
M2b	63	8	1	14.3
M3	66	12	2	21.2
M4	75	17	9	34.7

The highest shares of high and critical stress were found in M1b transformed mahalla development (74.8 %) and M1a traditional mahalla development (64.8 %). In M1b, this pattern is associated with transformation of the original low-rise fabric, increased building coverage, and reduction of internal open space. In M1a, much of the unbuilt land consists of private courtyards and gardens and is therefore not equivalent to publicly accessible recreational space. The distinction between private and publicly accessible green space is important when evaluating actual recreational accessibility [9].

The lowest shares were recorded in the microdistrict types: 16.8 % in M2a and 14.3 % in M2b. This may be related to the presence of large inter-building spaces and the remaining spatial reserve of the microdistrict structure. The role of open inter-building spaces as a structural element of mass housing is also emphasized by Dragutinovic, Quist, and Pottgiesser [2]. However, continued infill development may gradually reduce this reserve.

Morphotype M3 occupies an intermediate position, with high and critical stress affecting 21.2 % of the analysed units. For M4, the corresponding share is 34.7 %. Although M4 is characterized by the highest development intensity, it does not show the highest stress level. This indicates that spatial and environmental stress is not linearly determined by density, but depends on the combined effects of density, permeability, open-space structure, and recreational accessibility.

The particularly high stress observed in mahalla types contrasts with the more favorable distribution in microdistrict types M2a and M2b, supporting a morphotype-specific approach to densification regulation.

Table 3.

Priority planning measures by morphotype

Morphotype	Priority measure
M1a	Develop local public and recreational spaces and improve pedestrian connectivity
M1b	Limit uncontrolled densification and preserve internal open spaces
M2a	Preserve courtyards and green areas and control new infill development
M2b	Compensate densification through landscape improvements and maintain pedestrian connections
M3	Improve site permeability and the quality of courtyard spaces
M4	Integrate residential complexes into the surrounding urban fabric and ensure recreational accessibility

These priorities are consistent with approaches that link urban environmental quality to accessibility, connectivity, and the organization of public space [10].

Conclusion

The integrated assessment of 983 residential units in Tashkent revealed substantial differences in spatial and environmental stress among morphotypes. High and critical stress affected 48.0 % of the total sample, with the highest shares in transformed mahalla development M1b (74.8 %) and traditional mahalla development M1a (64.8 %), and the lowest in microdistrict types M2a (16.8 %) and M2b (14.3 %).

The results show that spatial and environmental stress is not linearly determined by development density, but emerges from the combined effects of morphometric characteristics, street-network connectivity, and recreational accessibility. Densification policies should therefore reflect the initial morphological structure of residential fabric: preserving open space and local connectivity in mahallas, protecting spatial reserves in microdistricts, and improving permeability and integration in contemporary mid- and high-rise developments. The proposed approach can be used as a preliminary diagnostic tool to identify areas where further densification requires restrictions or compensatory measures.

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Results of research on the application of laser methods for detecting wear particles in oil

Musurmanov Ravshan
doctor of Technical Sciences, Professor
National University of Uzbekistan named after M. Ulugbek
Uzbekistan, Tashkent

Utaev Sobir
PhD
in Technical Sciences, Associate professor
Karshi State University
Degree applicant at Tashkent Transport University
Uzbekistan, Tashkent

Turaev Abdugani
Mechanization Engineers, National Research University Tashkent Institute of Irrigation and Agricultural
Uzbekistan, Tashkent
E-mail: utaev.s@list.ru

Результаты исследования применения лазерных методов для обнаружения частиц износа в масле

Мусурманов Равшан
д-р техн. наук, проф.
Национальный университет Узбекистана имени М. Улугбека
Республика Узбекистан, г. Ташкент

Утаев Собир
канд. техн. наук
доц. Каршинский государственный университет, соискатель Ташкентский Транспортный университет
Республика Узбекистан, г. Ташкент

Тураев Абдугани
инженер-механик, Национальный исследовательский университет, Ташкентский институт инженеров ирригации и механизации сельского хозяйства
Республика Узбекистан, г. Ташкент

Abstract

This paper presents the results of an experimental study on the application of Laser-Induced Breakdown Spectroscopy (LIBS) for determining the concentration of wear products in used gas engine oil. It is shown that the main metallic components of wear particles are iron, copper, aluminum, chromium, and silicon. The LIBS method allows elemental analysis of wear products directly in the oil sample without complex sample preparation. It was found that at 100–200 engine operating hours, the particle size remains small and the content of wear products in the oil is relatively stable. With an increase in operating time to 300–400 hours, an increase in both the concentration of wear products and the size of metal particles is observed. A comparison of LIBS with traditional analytical methods (ICP-OES, atomic absorption spectrometry) was performed in terms of sample preparation, limit of detection, analysis speed, multi-element capability, and particle size analysis. The advantages of LIBS are demonstrated: minimal sample preparation, high analysis speed (less than 1 second), simultaneous multi-element determination, and the ability to analyze large particles (up to 100 µm). The results of the study can be used for non-disassembly diagnostics of gas and tractor engines based on the concentration of wear products in the oil.

Аннотация

В работе представлены результаты экспериментального исследования применения метода лазерно-искровой эмиссионной спектрометрии (LIBS) для определения концентрации продуктов износа в отработанном масле газовых двигателей. Показано, что основными металлическими компонентами частиц износа являются железо, медь, алюминий, хром и кремний. Метод LIBS позволяет проводить элементный анализ продуктов износа непосредственно в пробе масла без сложной пробоподготовки. Установлено, что при наработке 100–200 мото-часов размер частиц невелик, а содержание продуктов износа в масле относительно стабильно. При увеличении наработки до 300–400 мото-часов наблюдается рост как концентрации продуктов износа, так и размеров металлических частиц. Проведено сравнение LIBS с традиционными методами анализа (ICP-OES, атомно-абсорбционная спектрометрия) по таким параметрам, как подготовка проб, предел обнаружения, скорость анализа, возможность многоэлементного определения и размер анализируемых частиц. Показаны преимущества LIBS: минимальная пробоподготовка, высокая скорость анализа (менее 1 секунды), возможность определения всех элементов одновременно и анализа крупных частиц (до 100 мкм). Результаты исследования могут быть использованы для диагностики газовых и тракторных двигателей без их разборки по концентрации продуктов износа в масле.

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Keywords: aluminum, non-disassembly monitoring, wear products, laser, engine oil, spectrum, emission.

Ключевые слова: алюминий, неразборочный мониторинг, продукты износа, лазер, моторное масло, спектр, эмиссия.

Introduction

During the operation of gas engines, cylinder liners are subjected to high temperatures and pressures, leading to the formation of micro-irregularities on their working surfaces due to tribomechanical and tribological factors [1]. The cylinder-piston assembly is the main source of mechanical losses in an internal combustion engine and, according to literature data, accounts for up to 70 % of all friction losses [2]. Under the influence of high radial pressure from the piston rings, the oil film on the cylinder walls ruptures, which is accompanied by a significant increase in friction and accelerated wear of the cylinders and piston rings [3].

The method for determining the degree of wear based on the content of wear products in the oil relies on laboratory analysis of used oil. A sample taken from the engine crankcase after shutdown is thoroughly mixed and allowed to settle. Laboratory analysis allows the determination of the content of wear products, as well as organic and inorganic substances. This method does not require engine disassembly [3]. Laser methods enable the study of static, dynamic, vibrational, and other deformation processes, offering key advantages such as non-contact operation and simultaneous data acquisition [4, 5].

The aim of this work is an experimental study of the possibility of using Laser-Induced Breakdown Spectroscopy (LIBS) for the quantitative determination of wear product concentrations in used gas engine oils, as well as a comparative assessment of the effectiveness of this method with traditional analytical techniques (ICP-OES, atomic absorption spectrometry).

Materials and Methods

The research is based on existing analytical methods; theoretical approaches, standard techniques for determining wear products in oil, and mathematical statistical methods were employed.

Laser spectroscopy performs more effectively and accurately with gas-diesel oils compared to conventional diesel oils. Oil transparency decreases much more slowly due to lower soot content, allowing the laser beam to easily penetrate the sample and accurately measure the size of mechanical impurities and wear particles [6].

Modern reliability assurance is based on condition-based diagnostics; in particular, oil analysis — including wear debris, viscosity changes, and Total Base Number (TBN) — makes it possible to estimate the engine's remaining service life [7]. The probability of failure-free operation of engine oil is a measure of its ability to perform its intended functions without losing operational properties over a specific period of service [8].

To process the measurement results, mathematical statistical methods were used. The standard deviation and confidence interval were calculated for a pooled sample of 10 sequential measurements at a confidence level of P = 95 %. The results of the statistical processing are presented in the tables and in the graph.

Comparative characteristics of methods. The comparison of Laser-Induced Breakdown Spectroscopy (LIBS) with reference methods (ICP-OES, atomic absorption spectrometry) was performed according to the following parameters: sample preparation, limit of detection, analysis speed, multi-element capability, and particle size analysis [6, 9]. The comparison results are presented in Table 1.

Table 1.

Comparative characteristics of methods for analyzing wear products in oil

Characteristic	**LIBS**	**ICP-OES**	**Atomic Absorption Spectrometry**
Sample preparation	Absent or minimal. Direct drop analysis	Requires dilution with a solvent	Acid digestion, extraction, emulsion formation
Limit of detection	1–50 ppm (depends on element and matrix)	0.001–0.1 ppm	0.01–0.5 ppm
Analysis time	Less than 1 second	1–3 minutes per sample	1–2 minutes (one element at a time)
Multi-element capability	All elements simultaneously	Up to 40–70 elements simultaneously	Sequential analysis
Wear particle size	Dissolved and large particles up to 100 μm	>3–5 μm	Only fine/dissolved ones

Experimental setup and measurement conditions. Analysis of oil samples for wear product content was performed using Laser-Induced Breakdown Spectroscopy (LIBS) with a solid-state pulsed Nd:YAG laser. Laser parameters: wavelength λ = 1064 nm, pulse duration 5–10 ns, pulse energy 50–150 mJ, pulse repetition rate 1–10 Hz, focal spot diameter 50–200 μm [6, 9].

To ensure accurate determination of iron, aluminum, copper, chromium, and silicon particles in the oil, a double-pulse mode was used [10]. Measurement parameters: wavelength 1064 nm, pulse frequency 5 Hz, signal acquisition delay 1.0–2.5 μs, focal spot diameter 150 μm. Calibration was performed using a method simulating actual wear. The reliability of the results meets calibration quality assessment criteria with R^2 = 0.999 for dispersed particles of at least 0.095 μm.

To prevent wear particles from settling to the bottom, ultrasonic homogenization was used. Immediately before analysis, the sample was treated in an ultrasonic bath for 7 minutes to bring any sediment into suspension. To reduce viscosity, the engine oil sample was diluted with a solvent and applied in a thin layer onto a metal substrate. A series of 100 pulses was summed and averaged; based on the data obtained, the automated system generated a report containing the total elemental concentration in ppm (mg/kg) [9].

Sampling. Oil samples were collected after shutting down the operating gas engine. Measurements were performed in 5–10 replicates in accordance with ASTM D5185 and ASTM D6595 standards [9].

Results

Wear product content. During operational tests using the developed method, oil samples were collected in the required quantities. The content of wear products in used oil was determined under laboratory conditions. With increasing operating time, the amount of mechanical impurities and insoluble products increased (Table 2) [7, 8].

Table 2.

Results of oil analysis for wear product content using laser spectroscopy

Operating time, engine hours	Large particle size, µm	Small particle size, µm
100	29	16
200	52	30
300	68	42
400	79	56
500	82	62

Note: mean values from 10 measurements are presented. Measurement error (confidence interval at P = 95%) is ±15.8 µm.

Average particle size. Based on a pooled sample of 10 sequential measurements, the average particle size was $\bar{x}$ = 51.6 µm. The confidence interval at a confidence level of P = 95% is ±15.8 µm.

Dependence of wear product concentration on operating time. The concentration of wear products depends on the oil service life (Fig. 1). Wear metals (failure indicators): iron (Fe) indicates cylinder liner and camshaft wear; aluminum (Al) indicates piston wear; chromium (Cr) indicates piston ring wear [7, 8].

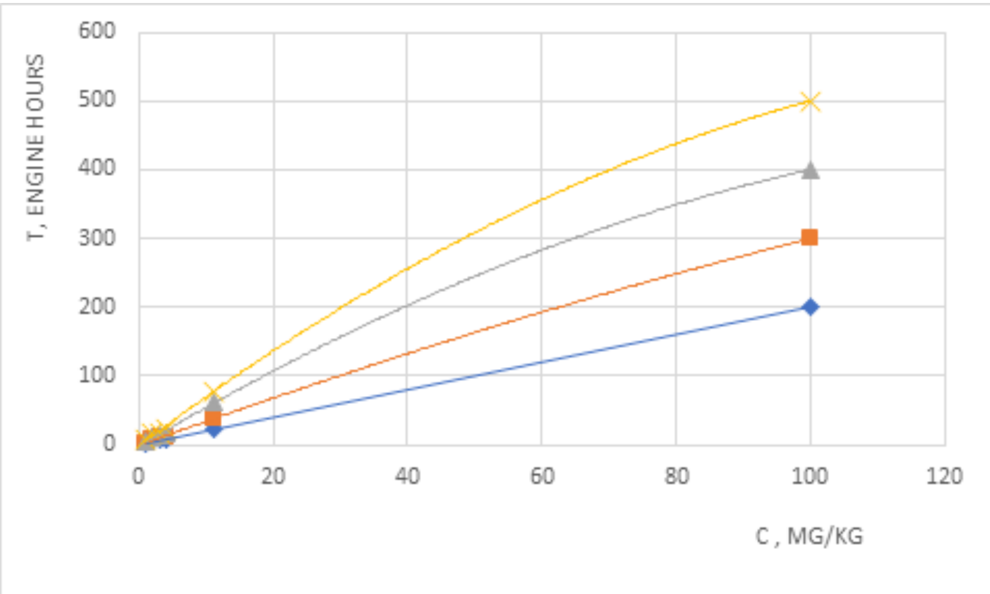

Figure 1. Dependence of wear product concentration in the oil on operating time

Fe, Ai Si Cr

Elemental composition of wear products. Analysis results indicate that the majority of particles consist of metals such as iron, copper, aluminum, chromium, and silicon [10]. In addition to these elements, metallic particles derived from oil additives were detected in the used gas engine oil. Iron constitutes the bulk of the wear products, contributing to the increase in total mass (Table 3) [7, 8].

Table 3.

Laser-induced breakdown spectroscopy analysis results

Element	Wavelength, λ, nm	Relative intensity, I_1/I	Concentration (mean), mg/kg	Absolute error, Δx
Iron, Fe	259.94	0.3050	42.2	±3.0
Aluminum, Al	396.15	0.0721	8.0	±0.60
Chromium, Cr	425.43	0.0252	3.6	±0.27
Silicon, Si	288.16	0.0917	12.8	±0.98

Interpretation of element concentrations. An increase in iron (Fe) concentration results from wear of cylinder liners, the camshaft, the crankshaft, and valve train gears [7]. An increase in aluminum (Al) concentration indicates wear of the piston and plain bearing shells (aluminum-tin). Chromium (Cr) content indicates wear of top compression piston rings (chrome plating) and valve stems. Copper (Cu) indicates wear of bearing shells (connecting rod, main), thrust washers, bronze bushings, and oil cooler. Silicon (Si) indicates ingress of dust through the air filter [8].

Discussion

The high relative standard deviation (RSD = 30.7 %) obtained during the study does not preclude the use of this method, as this result is due to physical factors and serves as an informative indicator of the presence of large particles [9]. The study results demonstrate the advantages of the LIBS method over traditional laboratory methods such as ICP-OES, RDE-AES, and XRF [6, 10].

When analyzing oil for wear products, it is necessary to consider both viscosity and chemical composition [6]. The standard viscosity for $M10G_2$ oil is 11 mm²/s; during operation, the viscosity of gas engine oil does not change significantly, typically remaining within the range of 9.5–10.2 mm²/s. At a measurement temperature of 20°C, the viscosity of such oil is approximately 110–140 mm²/s. Oils with a lower base viscosity (10 mm²/s) are more prone to spreading and hydrodynamic effects [9].

The chemical composition of the oil also influences the determination of wear products [10]. The heavy hydrocarbon matrix of mineral oil is prone to extensive thermal degradation (pyrolysis), and high concentrations of free radicals and molecular carbon compounds can form instantaneously in the plasma. Intense molecular emission bands appear in the LIBS spectrum, which can overlap with the analytical lines of wear metals, degrading the limit of detection, especially for iron (Fe) [6].

During operation, $M\text{-}10G_2$ oil degrades and its initially transparent appearance darkens. The resulting opaque black matrix drastically increases the optical absorption coefficient at the laser wavelength (1064 nm). As a result, the laser beam is not scattered within the droplet volume but is fully absorbed by the surface micro-film of the used oil. Due to this matrix change, the signal intensity for wear products (Fe, Cr) in darkened used oil will be 1.5–2 times higher than in fresh oil, even at the same actual concentration (in ppm) [9].

It should be noted that the LIBS method is insensitive to sample «age» provided that wear metals remain uniformly distributed throughout the oil volume [10]. However, over time, processes critical to metrology occur in the mineral oil sample: gravitational settling of large particles (>5–10 µm) within 48–72 hours; coagulation of soot during long-term storage (more than one month), trapping metal ions and increasing RSD to 25 % [7].

Recommended storage period: LIBS analysis should be performed within 7–10 days of sample collection [9]. Sample storage temperature affects oil viscosity and the rate of oxidative processes, thereby indirectly altering the quality of the laser plume. Low temperatures (–20…0°C) are considered ideal for long-term storage: freezing stops additive degradation and base oil oxidation, while metals become immobilized within the structure of the «solidified» oil. Prior to LIBS analysis, the sample must be fully warmed to +40°C and thoroughly mixed to restore homogeneity [8].

Conclusions

1. The study determined the effectiveness of Laser-Induced Breakdown Spectroscopy (LIBS) for analyzing the elemental composition of wear products in gas engine oils [6, 9]. The elemental concentrations in used oil were (mg/kg): iron (Fe) — 42.2, aluminum (Al) — 8.0, chromium (Cr) — 3.6, silicon (Si) — 12.8. The high iron concentration indicates wear of cylinder liners, camshaft, crankshaft, and valve train gears [7, 8].

2. Compared to traditional analysis methods (ICP-OES and atomic absorption spectrometry), the use of LIBS for analyzing wear products in gas engine oils provides high accuracy and comprehensive assessment of iron, copper, aluminum, chromium, silicon, and additive metals, while also delivering rapid results [6, 10].

3. Large wear particles (>5–10 µm) settle to the bottom of the container within 48–72 hours. If the oil sample is not ultrasonically agitated before being applied to the LIBS substrate, the instrument will report concentrations of Fe, Cr, and Cu that are 2–5 times lower than actual values [9].

4. Recommended storage period: LIBS analysis should be performed within 7–10 days of sample collection [9].

5. Sample storage temperature affects oil viscosity and the rate of oxidative processes, indirectly altering the quality of the laser plume. Low temperatures (–20…0°C) are considered ideal for long-term storage [8].

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Enhancing performance of mining piston compressors by optimizing cooling and lubrication systems

Xatamova Dilshoda Normorodovna
doctor of Technical Sciences (DSc)
professor, Professor of the Mining Engineering Department, Navoi State Mining and Technology University
Republic of Uzbekistan, Navoi

Abdixakimova Malika Amir qizi
Assistant
Department of Natural and Technical Sciences, Navoi Innovation University
Republic of Uzbekistan, Navoi
E-mail: aalusherov@gmail.com

Повышение эффективности поршневых компрессоров горнодобывающей промышленности путем оптимизации систем охлаждения и смазки

Хатамова Дилшода Нормородовна
д-р техн. наук (DSc)
проф., проф. кафедры горного дела, Навоийский государственный горно-технический университет
Республика Узбекистан, г. Навои

Абдихакимова Малика Амир кизи
ассистент
кафедра естественных и технических наук, Навоийский инновационный университет
Республика Узбекистан, г. Навои

Abstract

Objective: The objective of this study is to enhance the performance, efficiency, and reliability of mining reciprocating compressors by developing and optimizing advanced cooling descaling methods and improved lubrication filtration systems In practice, during the operation of reciprocating compressors, various problems arise related to the formation of scale and deposit

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layers on the heat exchange surfaces of air coolers, valve failures characterized by a low mean time between failures (MTBF), and the severe wear of moving parts such as the crosshead, shaft, and bearings, which ultimately leads to an increased number of emergency downtimes.

Methodology: SolidWorks Flow Simulation was utilized to evaluate the impact of scale thickness on cooling efficiency. Experimental setups were designed to test an ultrasonic acoustic device for descaling internal tube surfaces and to evaluate a novel porous magnetic oil filter.

Results: Simulation results demonstrated that each 1 mm increase in scale layer thickness decreases cooling effectiveness by 9 °C. Testing of the acoustic descaling device identified optimal parameters (15–20 kHz frequency, 1.5–2 ms pulse duration) for effective scale removal along long tubes. The proposed magnetic oil filter (70 % porosity, 10 mm thickness) achieved a 40–50 % higher oil purification efficiency compared to standard filters.

Conclusions: Implementing the optimized cooling and magnetic lubrication filtration systems drastically reduces emergency downtime, lowers energy consumption, and extends the operational lifespan of critical compressor mechanisms.

Аннотация

Цель: Целью данной работы является повышение производительности и надежности поршневых компрессоров горнодобывающей промышленности за счет оптимизации систем охлаждения и смазки. На практике в процессе эксплуатации поршневых компрессоров, возникают различные проблемы, связанные с образованием накипи и слоёв отложений на теплообменных поверхностях воздухоохладителей, поломки клапанов, которые имеют низкую наработку на отказ и интенсивный износ механизмов движения таких как крейцкопф, вал и подшипники, в результате которого увеличивается число аварийных простоев.

Методы: Для оценки влияния накипи на эффективность охлаждения применялось программное обеспечение SolidWorks Flow Simulation. Кроме того, были проведены экспериментальные исследования для определения оптимальных параметров ультразвукового акустического устройства для очистки от накипи и оценки новой конструкции магнитного масляного фильтра.

Результаты: Моделирование показало, что каждый 1 мм накипи снижает эффективность охлаждения на 9 °C. Экспериментальные испытания акустического устройства выявили оптимальные параметры (частота 15–20 кГц, длительность импульса 1,5–2 мс), обеспечивающие эффективное удаление отложений. Предложенный магнитный фильтр (пористость 70 %, толщина 10 мм) повысил эффективность очистки масла на 40–50 % по сравнению с базовыми фильтрами.

Выводы: Оптимизация систем охлаждения и смазки значительно снижает энергопотребление и увеличивает срок службы узлов компрессора.

Keywords: compressor, piston, cylinder, cooling system, air cooler, temperature, compressed air, reliability, lubrication system, oil filter, oil contamination.

Ключевые слова: компрессор, поршень, цилиндр, система охлаждения, воздухоохладитель, температура, сжатый воздух, надежность, система смазки, масляной фильтр, загрязненность масла.

1. Introduction

The operation of mining compressors is one of the most energy-intensive processes in the mining industry, necessitating effective resource conservation. In the overall energy balance of mining enterprises in Uzbekistan, the proportion of compressor equipment generating compressed air for pneumatic energy accounts for 20–25 %. Therefore, its further improvement significantly impacts the performance indicators of subsequent technological processes. The widespread application of compressed air dictates the need to reduce operating costs through the development of efficient technical solutions for industrial compressed air production, as well as the enhancement of the overall energy efficiency of compressor unit operations [1].

The cooling system has the most significant impact on the reduction of productivity and the increase in specific energy consumption of mining compressor units. Consequently, the efficiency of reciprocating compressor units can be improved by upgrading the cooling system, as energy losses due to insufficient cooling (undercooling) in reciprocating compressor units reach up to 20 %.

Furthermore, the failure-free and reliable operation of reciprocating compressors heavily depends on the lubrication system of the compressor's drive mechanisms. Special attention must be paid to the lubricating oil parameters and its purity, as the degradation of the initial oil characteristics and its contamination lead to the wear of moving friction components, thereby increasing the frequency of emergency shutdowns. Oil contamination causes wear on the shaft journal and its sections connected to the crank webs, leading to shaft deflection and premature failure. The operational performance of the crosshead, piston rod, and sliding blocks, which transmit the motion from the shaft to the piston, also depends on the purity and viscosity of the oil. The presence of abrasive particles in the lubricating oil leads to the wear of the crosshead, its slider surfaces, and the crosshead pin, resulting in a reduction of their dimensional tolerances and a decrease in their overall service life.

Currently, one of the primary challenges identified in the cooling systems of multi-stage reciprocating compressors is the inadequate cooling of air within the intercoolers and aftercoolers. The discharge pressure of the compressed air exiting the first stage of a reciprocating compressor typically ranges from 0.3 to 0.4 MPa, with temperatures reaching approximately 110–130 °C. It is necessary to reduce the temperature of the air being transferred from the first-stage cylinder to the second stage by roughly 70 °C. If the air temperature is not cooled to the specified requirement before entering the second stage, it may lead to emergency conditions. Moreover, a degradation in intercooler performance—where the air temperature remains 6–8 °C above the target—results in an increase in compression energy consumption of approximately 1 % [4].

The existing cooling systems for compressor machinery operated in the Kyzylkum region possess significant drawbacks due to their specific operational conditions. The cooling water contains high concentrations of salts and impurities. Typically, the total water hardness in the circulating cooling system exceeds 20 mg-eq/L, which is several times higher than permissible limits. Consequently, rapid fouling of the heat exchanger surfaces occurs. The accumulation of scale deposits reduces the intensity of heat transfer processes, compromising both the safety and economic efficiency of mining compressor operations.

The objective of this work is to enhance the performance and reliability of mining piston compressors by analyzing the factors reducing their efficiency and subsequently developing optimized cooling descaling techniques and advanced lubrication filtration systems.

2. Methodology

To determine the impact of scale thickness on air-cooling efficiency in the intercooler of a reciprocating compressor, a study was conducted using the advanced SolidWorks Flow Simulation software. The research analyzed compressed air discharge tcomp.air temperatures of 100°C, 110°C, 120°C, 130°C, and 140°C. The cooling water inlet temperature was set at 15°C, 20°C, and 25°C, while the scale layer σScale thickness was incrementally increased from 1 to 5 mm with a 1 mm step. The simulation was repeated for each air discharge tcomp.air temperature across the various cooling water t1cool wat temperatures and scale layer thicknesses.

To eliminate carbon deposits and scale on the heat exchange surfaces of air coolers during compressor operation—without requiring disassembly or additional labor—the application of an ultrasonic acoustic device is proposed.

The ultrasonic descaling device is applicable to various types of heat exchangers and operates as follows: special waveguide sensors (transducers) are mounted onto the acoustic wave generator, with the quantity determined by the total heat exchange surface area. The impulses generated by the ultrasonic device are transmitted through these sensors to the processed tube or heat exchanger. High-speed amplitude oscillations, with an average frequency of 12–25 kHz, are transferred to the walls of the heat exchanger, leading to the disintegration of the scale layer forming on the surfaces.

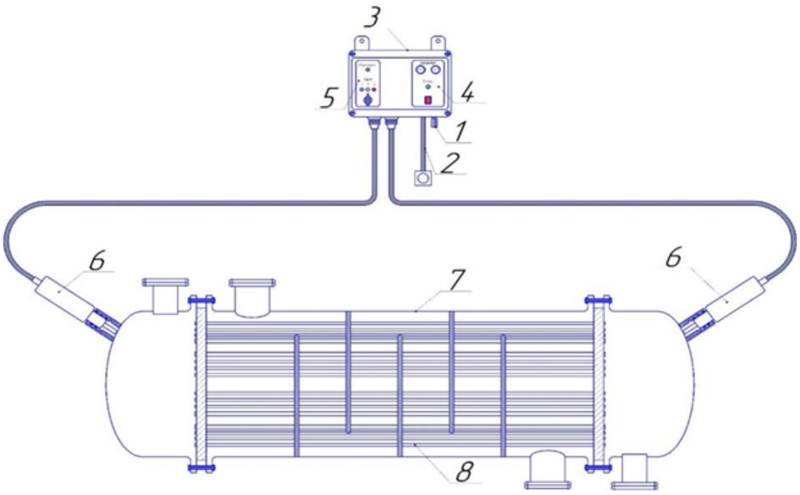


Figure 1. Connection schematic of the ultrasonic acoustic descaling device to the intercooler

(1 – grounding; 2 – power supply unit; 3 – housing; 4 – fuses and indicator; 5 – control panel; 6 – pulse transmission sensors; 7 – intercooler shell; 8 – pipelines)

The acoustic device developed in this study features adjustable pulse duration and oscillation frequency. Its technical specifications are summarized in the table below.

Table 1.

Technical specifications of the acoustic device

Power consumption, W	Acoustic power, W	Oscillation frequency, kHz	Pulse duration, ms	Impact area, m²	Number of sensors, pcs.
300	120	5-30	0.5-3	150	2-4

To ensure the effective descaling of the intercooler, experimental trials were conducted to determine the optimal oscillation frequency and pulse duration for the acoustic device. During the initial stage of the experiments, the scale delamination time from the test surface was measured across various pulse durations and amplitude-frequency characteristics. Acoustic treatment was applied to metal specimens with a uniform scale layer thickness. Within the ultrasonic device, the oscillation frequency was incrementally increased from 5 kHz to 30 kHz in 5 kHz steps, while the pulse duration was varied at levels of 1, 1.5, and 2 ms

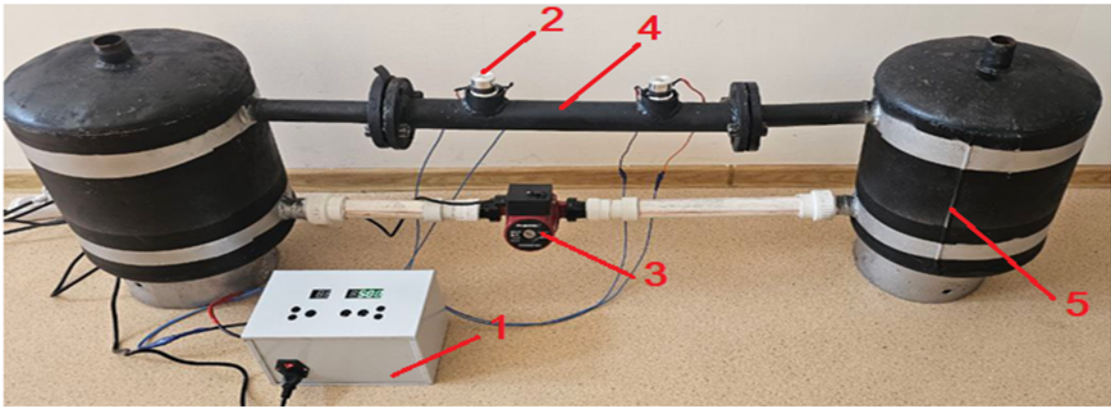


Figure 2. Experimental setup for investigating ultrasonic acoustic descaling of internal pipe surfaces

1 – ultrasonic device; 2 – ultrasonic transmitting sensors (transducers);

3 – pump; 4 – pipe; 5 – water tank.

To enhance oil filtration efficiency, a new oil filter design has been developed based on a porous filter media. This design allows for the high-quality purification of the circulating oil by capturing abrasive metallic particles as small as 0.5 mcm, while also allowing for the regeneration of the filter media. The distinctive feature of this design compared to other similar porous filters is its cylindrical configuration with a magnetic rod installed at the center. The filter media itself is dual-layered: the pore size of the layer adjacent to the magnetic rod is 0.5–1.0 mcm, while the pore size of the second (outer) layer is 3–5 mcm

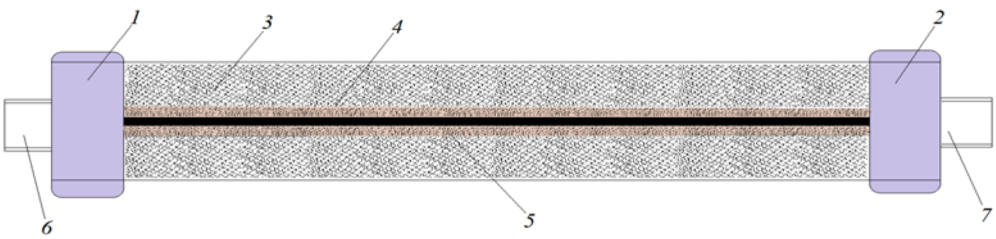


Fig.3. Design of the magnetic oil filter

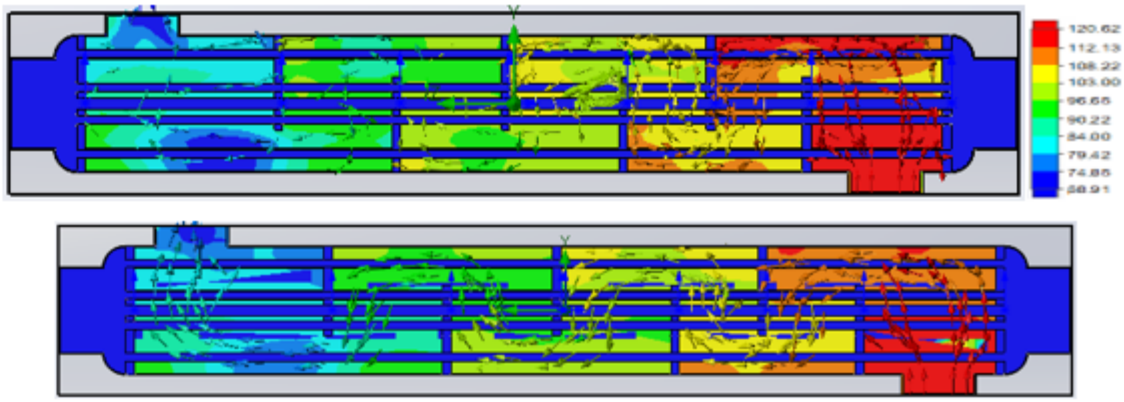
1, 2 – removable covers; 3 – filter media with a pore size of 3–5 μm;

4 – filter media with a pore size of 0.5–1.0 µm; 5 – permanent magnet;

6, 7 – connecting parts.

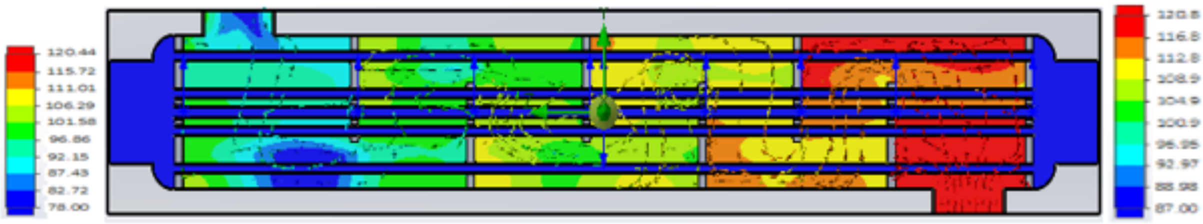
Two-stage experimental trials were conducted to evaluate the efficiency of the developed magnetic oil filter. In the first stage, 5 liters of KS-19 compressor oil, which had been in operation for 2,500 operating hours, were filtered. The oil contained metallic particles ranging from 880 to 900 mg/kg with particle sizes between 0.5 and 25 mm. Filtration was performed using a standard porous filter with porosities of 40 %, 50 %, 60 %, and 70 % under a pressure of 4 bar. In the second stage, the proposed magnetic oil filter was tested. These experiments involved varying the thickness of the filter media surrounding the magnet (5, 10, and 15 mm) across the same porosity levels (40 %, 50 %, 60 %, and 70 %).

3. Results and Discussion

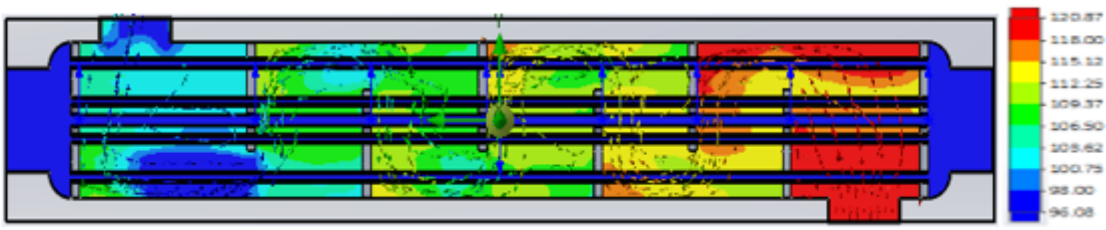


a) $t_{comp.air} = 120^{\circ}C$; $t_{1cool\ wat} = 20^{\circ}C$; $\sigma_{Scale} = 0\ mm$.

b) $t_{comp.air} = 120^{\circ}C$; $t_{1cool\ wat} = 20^{\circ}C$; $\sigma_{Scale} = 1\ mm$.



c) $t_{comp.air} = 120^{\circ}C$; $t_{1cool\ wat} = 20^{\circ}C$; $\sigma_{Scale} = 2\ mm$



d) $t_{comp.air} = 120^{\circ}C$; $t_{1cool\ wat} = 20^{\circ}C$; $\sigma_{Scale} = 3\ mm$

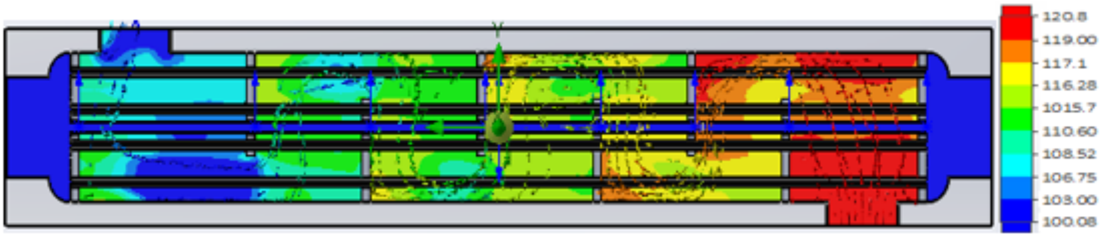


Figure 4. Simulation results illustrating the impact of scale layer thickness on cooling efficiency, obtained using SolidWorks Flow Simulation

e) $t_{comp.air} = 120°$; $t_{1cool\ wat} = 20°C$; $\sigma_{Scale} = 4\ mm$.

The research results indicate that for every 1 mm increase in scale layer σScale thickness on the inner walls of the cooler tubes, the compressed air cooling effectiveness decreases by 9 °C. This trend remains consistent until the scale thickness reaches 4 mm. Once the scale layer thickness reaches 4 mm or more, each subsequent 1 mm increase in scale results in a further reduction in cooling effectiveness by 2–4 °C

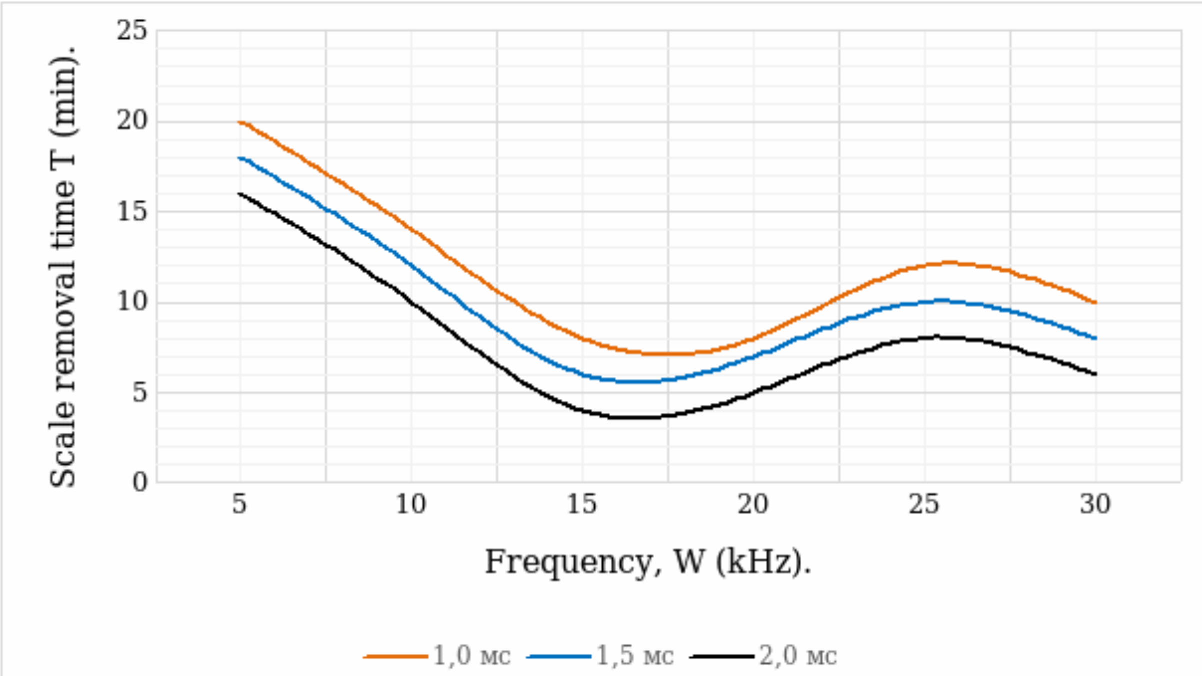


Figure 5. Dependence of descaling time on oscillation frequency and pulse duration generated by the acoustic device

The experimental results established that when using the proposed ultrasonic acoustic descaling device, the most efficient and rapid removal of scale from metallic surfaces is achieved at an oscillation frequency of 15–20 kHz and a pulse duration of 2 ms

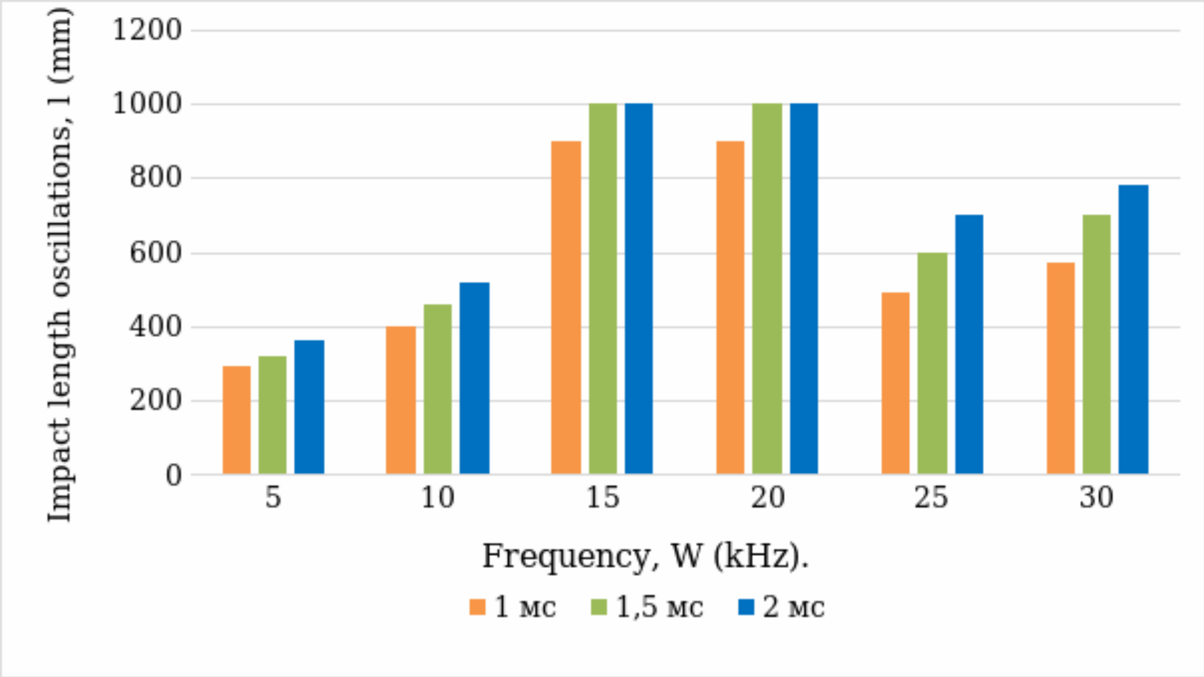


Figure 6. Dependence of oscillation amplitude, oscillation frequency, and pulse duration on pipe length

An analysis of the experimental results regarding the effective application of the acoustic descaling device for internal tube surfaces leads to the conclusion that for tubes with a length of 1000 mm or more, an oscillation frequency within 15–20 kHz and a pulse duration of 1.5–2 ms must be maintained to achieve high efficiency. The practical implementation of this device has resulted in improved cooling efficiency of the compressed air within the intercoolers of the reciprocating compressor [16, p. 38].

Regarding the lubrication system, the experimental results indicated that the integration of a magnetic rod into the porous filter media reduces the oil flow velocity. For instance, the oil flow velocity through a standard filter with 70 % porosity is 75 mm/s, whereas the velocity through the magnetic filter with the same porosity and a 5 mm media thickness is 50 mm/s. The flow velocity is further influenced by the thickness and porosity of the magnetic surface filter. However, the reduction in oil flow velocity within the magnetic filter is compensated by its significantly enhanced cleaning capacity (filtration efficiency).

The optimal parameters for the proposed magnetic filter were determined to be a 70 % porosity and a 10 mm thickness. These parameters ensure maximum oil purity and the highest achievable flow velocity while maintaining the ability to capture sub-micron particles (less than 1 mm) contained within the oil

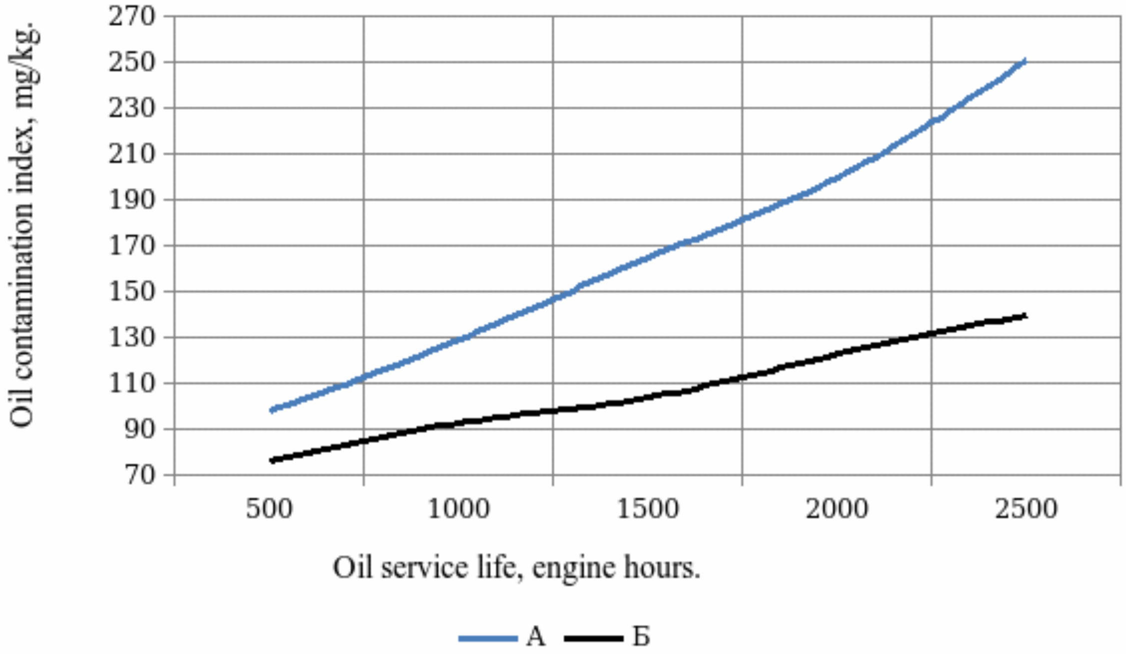


Figure 7. Dependence of oil contamination increase on operating time using the baseline (A) and proposed (B) filters

A comparison between the baseline and magnetic filters established that the proposed magnetic filtration system is approximately 40–50 % more effective at purifying the oil.

4. Conclusion

Based on the research conducted, the following conclusions of theoretical and practical significance have been drawn:

1. Each 1 mm increase in scale thickness on the heat exchange surfaces of the intercoolers in multi-stage reciprocating compressors leads to an average 5 % increase in the temperature of the air delivered to the next stage cylinder.

2. An ultrasonic acoustic device has been developed, enabling the effective descaling of the intercooler heat exchange surfaces in multi-stage reciprocating compressors. The practical application of this device has resulted in a 95 % reduction in scale formation within the air coolers and a 2 % reduction in energy consumption for air compression.

3. The optimal values for oscillation amplitude, frequency, and pulse duration generated by the ultrasonic acoustic device have been determined (frequency 15–20 kHz, pulse duration 1.5–2 ms), ensuring effective descaling of the internal surfaces of metallic tubes.

4. The optimal parameters for the improved design of the compressor lubrication system filter have been established. A porosity of 70 % and a filter media thickness of 10 mm over the magnet ensure maximum oil purity and the highest flow velocity, while achieving the capability to capture sub-micron particles (less than 1 mcm) contained in the oil.

5. The implementation of the improved filter design in the compressor lubrication system allows for an increase in the service life of the crosshead by 20 %, the oil pump by 30 %, the connecting rod by 20 %, and both the oil filter and the lubricant itself by 60 %.

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ECOLOGY AND SAFETY

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ASsessment of long-term changes in groundwater mineralization in the irrigated lands of the Republic of Karakalpakstan

Khojamuratova Roza Tazhimuratovna
professor
Berdakh Karakalpak State University
Republic of Uzbekistan, Republic of Karakalpakstan, Nukus
E-mail: hroza71@gmail.ru

Jangabaev Daniyar Mansurovich
Research University of Irrigation and Water Problems, Independent researcher
Republic of Uzbekistan, Republic of Karakalpakstan, Khojeyli
E-mail: danijangabaev@gmail.com

Оценка долгосрочных изменений минерализации грунтовых вод на орошаемых землях Республики Каракалпакстан

Хожамуратова Роза Тажимуратовна
проф.
Каракалпакский государственный университет имени Бердаха, Республика Узбекистан
Республика Каракалпакстан, г. Нукус

Жангабаев Данияр Мансурович
независимый исследователь, Научно-исследовательский университет ирригации и водных проблем, Республика Узбекистан
Республика Каракалпакстан, г. Ходжейли

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Abstract

The article examines the problems of studying, analyzing, and monitoring existing data on the hydrogeological, hydroecological, and reclamation state of groundwater dynamics in the irrigated lands of the Republic of Karakalpakstan. The research focuses on long-term changes (1990–2019) in groundwater levels and mineralization across 14 administrative districts of the Amu Darya delta, based on long-term observation data of the reclamation service of the Ministry of Water Resources of the Republic of Uzbekistan. Special attention is paid to the influence of intensive irrigation, filtration losses from the Amu Darya River, and anthropogenic factors on the hydrochemical regime and salinization processes of irrigated soils. Analysis of observational data showed that groundwater levels fluctuate significantly during the vegetation period, with the highest levels observed during leaching irrigations in spring. The predominant mineralization range is 1–3 g/l, occupying about 85 % of irrigated lands, a share consistent with recent basin-wide assessments. However, in some districts, mineralization reaches critical levels, exceeding permissible standards for irrigation water and contributing to secondary salinization. A statistical analysis (Pearson correlation, $r = 0.75$, $R^2 = 0.56$, $p = 0.002$) confirmed a significant positive relationship between average groundwater depth and mineralization across districts, reflecting reduced flushing and greater evaporative concentration of salts in poorly drained peripheral areas. The study reveals the main sources of groundwater recharge and discharge, the heterogeneity of hydrogeological conditions, and the role of natural and anthropogenic factors in salt accumulation. Practical recommendations are proposed for improving hydrogeological and hydroecological monitoring systems, optimizing irrigation and drainage networks, and reducing water losses to prevent further degradation of irrigated lands. These findings are essential for sustainable water resources management and increasing agricultural productivity in the arid conditions of Karakalpakstan.

Аннотация

В статье рассматриваются вопросы изучения, анализа и мониторинга имеющихся данных о гидрогеологическом, гидроэкологическом и мелиоративном состоянии динамики грунтовых вод на орошаемых землях Республики Каракалпакстан. Основное внимание уделено долгосрочным изменениям (1990–2019 гг.) уровня и минерализации грунтовых вод по административным районам дельты Амударьи. Особое внимание уделено влиянию интенсивного орошения, фильтрационных потерь из реки Амударья и антропогенных факторов на гидрохимический режим и процессы засоления орошаемых почв. Анализ данных наблюдений показал, что уровень грунтовых вод существенно колеблется в течение вегетационного периода, при этом наивысшие уровни отмечаются во время весенних промывных поливов. Преобладающий диапазон минерализации составляет 1–3 г/л и занимает наибольшую площадь орошаемых земель (около 85 %). Однако в отдельных районах минерализация достигает критических значений, превышающих допустимые нормы для оросительной воды, что способствует вторичному засолению. Статистический анализ (коэффициент корреляции Пирсона $r = 0{,}75$; $p = 0{,}002$) подтвердил значимую положительную связь между глубиной залегания и минерализацией грунтовых вод по районам. Исследование выявляет основные источники питания и разгрузки грунтовых вод, неоднородность гидрогеологических условий, а также роль природных и антропогенных факторов в накоплении солей. Предложены практические рекомендации по совершенствованию систем

гидрогеологического и гидроэкологического мониторинга, оптимизации ирригационно-дренажных сетей и снижению потерь воды для предотвращения дальнейшей деградации орошаемых земель. Полученные результаты имеют важное значение для устойчивого управления водными ресурсами и повышения продуктивности сельского хозяйства в засушливых условиях Каракалпакстана.

Keywords: Amu Darya delta, groundwater mineralization, hydrochemical regime, hydroecological monitoring, hydrogeological monitoring, salinization, anthropogenic factors, statistical analysis.

Ключевые слова: дельта Амударьи, минерализация грунтовых вод, гидрохимический режим, гидроэкологический мониторинг, гидрогеологический мониторинг, засоление, антропогенные факторы, статистический анализ.

Introduction

Groundwater salinization and mineralization in the Amu Darya delta remain among the most pressing environmental problems of Central Asia and reflect a broader global groundwater crisis [13]. Recent district-level assessments show that in the Amudarya district alone the majority of irrigated land is affected by soil and groundwater salinity, with a substantial share classified as moderately to highly saline [8]. Comparable studies in the neighboring Khojeyli district have documented shallow, highly mineralized groundwater linked to irrigation return flow and insufficient drainage [5], while GIS-based approaches are increasingly used to map the spatial extent of salinized soils across Karakalpakstan [6]. Basin-wide climate-risk assessments further report that groundwater with mineralization of 1–3 g/l already covers more than 85 % of irrigated land in the Amu Darya river basin [16], a pattern that studies of secondary salinization attribute largely to reduced natural flushing of the lower delta [7]. Despite this growing body of work, systematic, multi-decade comparisons of groundwater level and mineralization dynamics across all administrative districts of the Republic of Karakalpakstan remain scarce, which limits the ability of water management agencies to prioritize districts for remediation.

The geological structure of the Amu Darya delta on the territory of the Republic of Karakalpakstan consists of various types and kinds of deposits from the Cretaceous, Tertiary, and Quaternary periods. Cretaceous deposits occur on the right bank of the river. Tertiary deposits are found near Tuyamuyun, the Kyzylkum Desert, the Ustyurt Plateau, and in other areas in the form of red and red-yellow clays.

Quaternary deposits are widely distributed throughout the territory of the modern and forming Amu Darya delta. They consist of sands, sandy loams, loams, and clays transported by water. These deposits are characterized by relatively good permeability, loose structure, and instability to flooding processes. Quaternary deposits serve as the main object of reclamation, within which groundwater is formed and its regime develops. Comparable patterns of groundwater formation in arid and super-arid deltaic environments of Central Asia and the Arabian Peninsula have been described elsewhere [11], and drought-related groundwater dynamics in Karakalpakstan were documented following the severe drought of 2001 [12].

Building on this background, the aim of this study is to assess long-term changes in groundwater levels and mineralization in the irrigated lands of the Republic of Karakalpakstan and to identify the main natural and anthropogenic factors influencing the salinization of irrigated soils. To achieve this aim, the following objectives were addressed: (1) reviewing the geological and hydrogeological structure of the Amu Darya delta; (2) analyzing groundwater level and mineralization dynamics across administrative districts for the period 1990–2019, including a statistical assessment of the relationship between depth and mineralization; (3) comparing the results with published regional and international studies; and (4) formulating practical recommendations for improving hydrogeological and hydroecological monitoring of irrigated lands.

Materials and Methods

In the course of the work, materials were collected on the depth of occurrence (groundwater level, GWL) and mineralization of groundwater in the irrigated territory, by administrative districts of the Republic of Karakalpakstan, for the period from 1990 to 2019, based on data from the reclamation service of the Ministry of Water Resources of the Republic of Uzbekistan. Groundwater level and mineralization data were obtained from the standing network of observation (piezometric) wells maintained by the reclamation service across the 14 administrative districts, with measurements taken seasonally during the irrigation period. Groundwater mineralization was determined by the dry-residue method routinely applied by the reclamation service laboratories and is expressed in g/l.

Groundwater depth and mineralization were compared against the classification of groundwater flow groups after N.N. Khodjibaev; the regional groundwater balance structure of the entire delta is presented and discussed in the Results section (Table 1). Hydrochemical data were further evaluated against the applicable water-quality standards — «Drinking Water» and «Water for Irrigation» — and the list of maximum permissible concentrations (MPC) of the NIGMI Institute and the classification of the Scientific-Research Institute of Irrigation and Water Problems. Recommended irrigation-water salinity thresholds by crop-tolerance class, following the international FAO classification, were also used for comparison (Table 3) [14].

To characterize the relationship between average groundwater depth and mineralization at the district level, Pearson's correlation coefficient and simple linear regression were calculated across the 14 administrative districts for which data were available; statistical significance was assessed at $p < 0.05$ (Figure 2).

Results and Discussion

Analysis of the available data on the hydrogeological and reclamation conditions regarding the dynamics of groundwater in irrigated lands has shown that high groundwater levels are observed in March and April, during the period of intensive leaching irrigations. After the completion of leaching, a certain decline in the level occurs.

In terms of groundwater formation conditions, the lower reaches of the Amu Darya River differ from other oases in Uzbekistan in that the main river artery here runs along commanding elevations of the territory, forming groundwater flows moving from the river into the depths of the oasis.

On the irrigated area of 515.3 thousand hectares, groundwater at a depth of 0–1 m occupies 7.8 thousand ha; 1–1.5 m — 48.9 thousand ha; 1.5–2 m — 267.8 thousand ha; 2–3 m — 120.9 thousand ha; 3–5 m — 66.9 thousand ha; and more than 5 m — 2.25 thousand ha. Groundwater mineralization varies as follows: 0–1 g/l occupies 2.7 thousand ha; 1–3 g/l occupies 439.7 thousand ha (about 85 % of the irrigated area); 3–5 g/l — 72.8 thousand ha; 5–10 g/l — 6.06 thousand ha; and more than 10 g/l — 0.3 thousand ha. The uneven distribution of irrigated land within the predominant 1–3 g/l mineralization range among districts is illustrated in Figure 1.

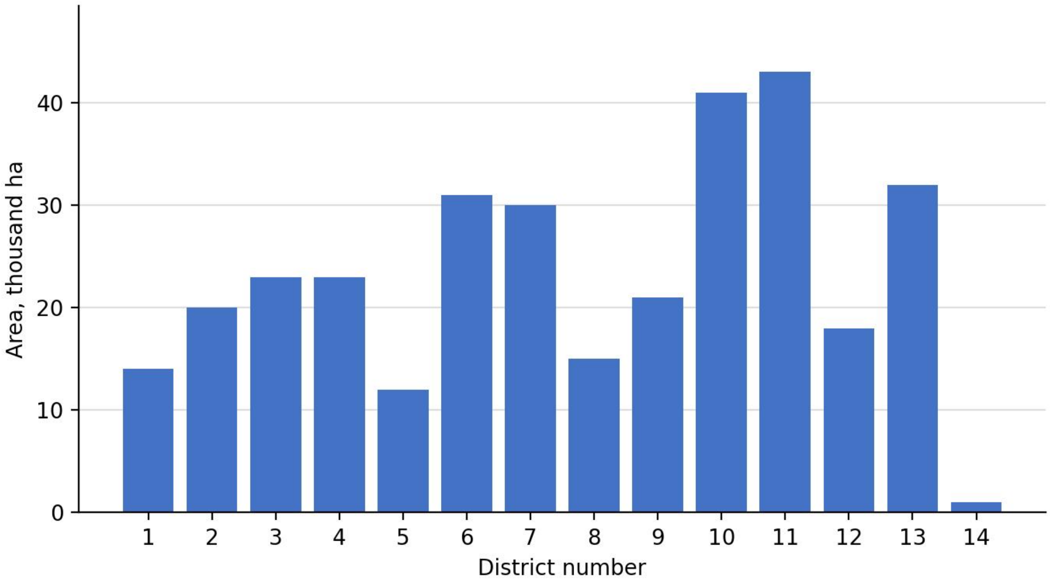

Figure 1. Area of irrigated land (thousand ha) with groundwater mineralization of 1–3 g/l by administrative district of the Republic of Karakalpakstan, averaged over the vegetation period of 2018

District numbers: 1 — Tortkul, 2 — Ellikkala, 3 — Beruni, 4 — Amudarya, 5 — Khojeyli, 6 — Shumanay, 7 — Kanlykul, 8 — Kungrad, 9 — Nukus, 10 — Kegeyli, 11 — Chimbay, 12 — Karaozyak, 13 — Takhtakupyr, 14 — Muynak.

Groundwater saturating the thickness of deltaic deposits and almost devoid of general runoff forms an extensive basin with heterogeneous hydrogeological conditions. This heterogeneity is expressed in differences in the depth of groundwater occurrence, their mineralization, and conditions of local runoff, depending on recharge, relief, and lithological composition of the rocks.

In the formation of delta groundwater, the river itself and its tributaries play the main role. Atmospheric precipitation contributes a noticeable share to groundwater recharge only in spring on areas with shallow occurrence. Groundwater is mainly consumed by evaporation. Underground runoff is of subordinate importance, depending on local lithological and geomorphological conditions. Areas with more or less well-expressed local underground runoff are located near the river and its tributaries [1–3].

Peripheral parts of the delta, near the Ustyurt Plateau in the west and in the Takhtakupyr district in the east, are characterized by usually deep groundwater occurrence (below 10 m), where evaporation is extremely weakened.

Within the areas near the Aral Sea, characterized by an abundance of frequently changing river channels, floods, and lakes, groundwater occurs at shallow depths (usually no deeper than 3 m). Local underground runoff in these parts of the delta is noticeably expressed along active channels (of the river and its tributaries), which serve as sources of groundwater recharge. The underground runoff directed from the channels into the depth of the coastal strip quickly attenuates (at tributaries within several hundred meters, and at the main river channel — 1–2 km), since in most cases it occurs under conditions of shallow groundwater occurrence, which evaporates in significant quantities along the flow path.

The structure of the regional groundwater balance of the entire delta from Tuyamuyun to the Aral Sea (without taking irrigation into account) characterizes the basin as a territory of natural salt accumulation and is presented in Table 1.

Groundwater mineralization in the stagnation zone is variegated; an uneven distribution of salts is observed, which mainly depends on the presence of local underground runoff [2–3].

Table 1. Structure of the regional groundwater balance (m^3/s) of the entire delta from Tuyamuyun to the Aral Sea (without taking irrigation into account), which characterizes the basin as a territory of natural salt accumulation.

Income	Value	Expenditure	Value
Losses from the Amu Darya River (excluding overflow)	320	Underground runoff	0
Atmospheric precipitation	30	Total evaporation, rise in groundwater levels, and return to the river	350
Underground tributary	0		
Total	**350**		**350**

The lowest mineralization is characteristic of groundwater in the near-river strip and areas adjacent to the channels. Hydrocarbonate-sulfate calcium waters predominate here, while directly near watercourses, hydrocarbonate calcium waters are prevalent. As the total salt content in the water increases — particularly sharply expressed in the middle parts of inter-channel depressions — the content of sulfates and chlorides rises. In highly mineralized waters (40–60 g/l), chlorides predominate. Among cations, sodium and magnesium are dominant.

In the vertical profile, groundwater mineralization is also variable. It is freshened by filtration waters of the Amu Darya River and its tributaries through local underground runoff. Finally, saline, especially Tertiary, rocks of the bedrock often cause increased mineralization of groundwater in the lower part of the aquifer. Therefore, in some cases, mineralization decreases with depth, while in others it increases.

When considering the conditions of groundwater occurrence, it is easy to notice the specific structure of the aquifer in deltaic deposits. Sandy formations of channel facies are widely developed within the delta body. As a result of the wandering of the river and its tributaries, channel facies were buried under flood and lake facies, represented by a layered complex of sandy loams, loams, and clays containing interlayers of fine-grained sand. Channel deposits within the delta body have a multi-tiered structure.

Due to the variability of the hydrographic network directions throughout its development history, the horizontal projections of ancient buried and modern channels intersect in a complex manner.

Channel facies are of great interest as potential sites for natural collectors (in the case of creating a regional lowering of the groundwater table through well pumping). These areas are also the most favorable for the localization of underground, albeit weak, runoff.

According to the works of N.N. Khodjibaev, several groups of groundwater flows are distinguished in the basin territory.

A. Group of groundwater flows of the left bank of the Amu Darya. It is located in the western part of the basin, on the territory of the Priaral part of the Amu Darya delta. Its boundaries in the east and southeast run along the Amu Darya, in the south — along the outcrops of bedrock through the «Nazymkhan» protrusion to the «Akkelin» plateau, in the west along the chink of the Ustyurt, in the northwest along the 40th hydroisohypse, which is the boundary of the described flow with the groundwater flow from Lake Sudochye, and in the north (conditionally) along the line of the modern forming delta.

Sources of groundwater recharge are filtration losses of surface runoff and infiltration of atmospheric precipitation. In some areas in old channels, in Cretaceous and Quaternary deposits, lenses of fresh water with mineralization up to 1 g/l are observed. Groundwater mineralization increases from the recharge zone to the discharge zone from fresh to brackish-saline (from 0.5 to 50–60 g/l).

B. Group of groundwater flows of the modern Aral delta. It is located in the northwestern part of the basin. In the west it is bounded by the Amu Darya, in the north by the modern forming delta, in the northeast the boundary runs along the southwestern slope of the Beltau upland, and in the southeast along the Tabakum sands. Sources of groundwater recharge are filtration waters of temporarily and permanently operating watercourses and, to some extent, infiltration of atmospheric precipitation.

The depth of groundwater occurrence varies from 1–5 to 10–20 m. Mineralization changes from 0.5 g/l (in the recharge zone) to 10–50 g/l (in the discharge zone). In the area of this group of flows, the process of vertical water exchange predominates. The territory is naturally poorly drained, and in the lower part, where evaporation predominates over runoff, it is undrained.

Group of groundwater flows of the northern slopes of the Sultan-Uiz-Dag Mountains. It is located in the southeastern part of the described basin. Sources of groundwater recharge are surface waters of the Amu Darya, atmospheric precipitation, and overflow from bedrock deposits. The waters are characterized by low mineralization (from 0.5 to 1.5 g/l) in the old channels of the Amu Darya and increased mineralization (up to 10–15 g/l) on the sandy plain [2–4]. In the recharge zones, groundwater occurs at elevations of 95–105 m, and in the discharge zones — at 40 m. The direction of flow movement is from south to north and northeast. Due to hindered underground runoff and the climatic conditions of the area, groundwater is mainly consumed by evaporation and plant transpiration. A small amount of water is discharged as underground outflow toward the Sarykamysh depression. Outflow is somewhat improved along the channels of old riverbeds.

The mineralization of groundwater in the oasis depends on the nature of groundwater recharge and discharge and their connection with the river. Mineralization varies from 0.5 to 5 g/l and higher. The least mineralized waters are developed along the Amu Darya old channels of Daryalyk and

Daudan, while the most mineralized waters are mainly distributed beyond the oasis. This indicates a significant movement of water masses, and consequently salts, within the delta under the influence of natural geological factors.

The hydrochemical profile throughout the territory of the Pri-Sarykamysh delta has one form: a certain increase in mineralization at the groundwater table, a decrease in the interval of 5–15–25 m, and an increase again with depth.

In terms of chemical composition, groundwater changes from hydrocarbonate-sulfate to chloride-sulfate types. The ratio of groundwater recharge to evaporation determined the features of the chemical composition — intensive accumulation of chlorides in the oasis groundwater.

For the basin territory, the distribution of groundwater with a table depth from 1–2 to 30 m is characteristic. The closest occurrence of the level is observed in the near-Amu Darya strip; with distance toward its periphery, it deepens, and in the desert part of the delta it is at a depth of over 15 m.

Groundwater discharge on the left bank occurs due to evaporation, transpiration, and underground outflow toward the Sarykamysh depression, partially by wedging out in the area of lakes in southern Khorezm. In the Akchadarya delta, discharge occurs through evaporation, transpiration, and partially by wedging out into Lake Ashikkul.

According to data from the reclamation service of the Ministry of Water Resources of the Republic of Uzbekistan, lands with medium and strong degrees of salinization in the Republic of Karakalpakstan constituted 40 to 50 % of the irrigated territory in different years, with strong salinization ranging from 22.7 to 64.5 thousand ha (in Khorezm — from 12 to 39 thousand ha). If such lands are left without leaching, it is generally impossible to obtain a harvest. Seasonal salinization depends on groundwater depth, irrigation regime, and technology during cotton vegetation, typically intensifying toward the end of the vegetation period as evaporative concentration of salts in the upper root zone increases; comparable seasonal water-salt regime patterns and the need for regulated leaching and drainage have been described in other Karakalpakstan and Khorezm studies [9, 10, 15]. With insufficient supply of irrigation water from above and unsatisfactory drainage of territories, salts accumulate in the upper root zone by the end of the vegetation period. Salinization is the result of suboptimal water resources management, leading to significant losses in the yield of cotton and other agricultural crops. Unsatisfactory drainage contributes to groundwater stagnation, but the main reason for the rise in groundwater levels is large water losses from canals and fields during irrigation of agricultural crops.

The average groundwater level and mineralization in the irrigated zone of the Republic of Karakalpakstan by administrative district (2018 and recent years) are summarized in Table 2. It is evident that within reclamation systems, the average annual groundwater level varies from 133 to 743 cm. It should be noted as a limitation of this study that district-level observation data for Khojeyli district were not available for the analyzed period; this district is therefore omitted from Table 2, and closing this gap is recommended as a direction for future monitoring and follow-up research.

Table 2.

Average groundwater level and mineralization by administrative district of the Republic of Karakalpakstan

District	Groundwater level range, cm	Average annual mineralization, g/l
Tortkul	171–235	3.08
Ellikkala	179–258	2.46
Beruniy	133–195	2.78
Amudarya	137–188	2.63
Shumanay	179–488	3.12
Kanlykul	160–428	2.62
Kungrad	176–378	2.29
Muynak	252–743	6.00
Nukus	185–297	2.33
Kegeyli	165–365	2.98
Buzatau	215–485	2.98
Chimbay	172–390	3.29
Karaozyak	175–452	2.93
Takhtakupyr	192–411	2.49
Republic-wide average	185–357	3.00

Statistical analysis. Across the 14 districts for which data were available, average groundwater depth (midpoint of the reported range) and average mineralization show a moderate-to-strong, statistically significant positive correlation (Pearson $r = 0.75$; $R^2 = 0.56$; simple linear regression: mineralization (g/l) = 0.008 × depth (cm) + 0.77; $p = 0.002$, $n = 14$; Figure 2). This indicates that districts with deeper and more variable groundwater tables — such as Muynak, where levels fluctuate between 252 and 743 cm — tend to have higher mineralization, consistent with reduced flushing, longer residence time, and greater evaporative concentration of salts in poorly drained peripheral areas of the delta. In contrast, districts with the shallowest, near-river groundwater, such as Amudarya and Beruni, show comparatively lower mineralization, consistent with active freshening by filtration losses from the Amu Darya.

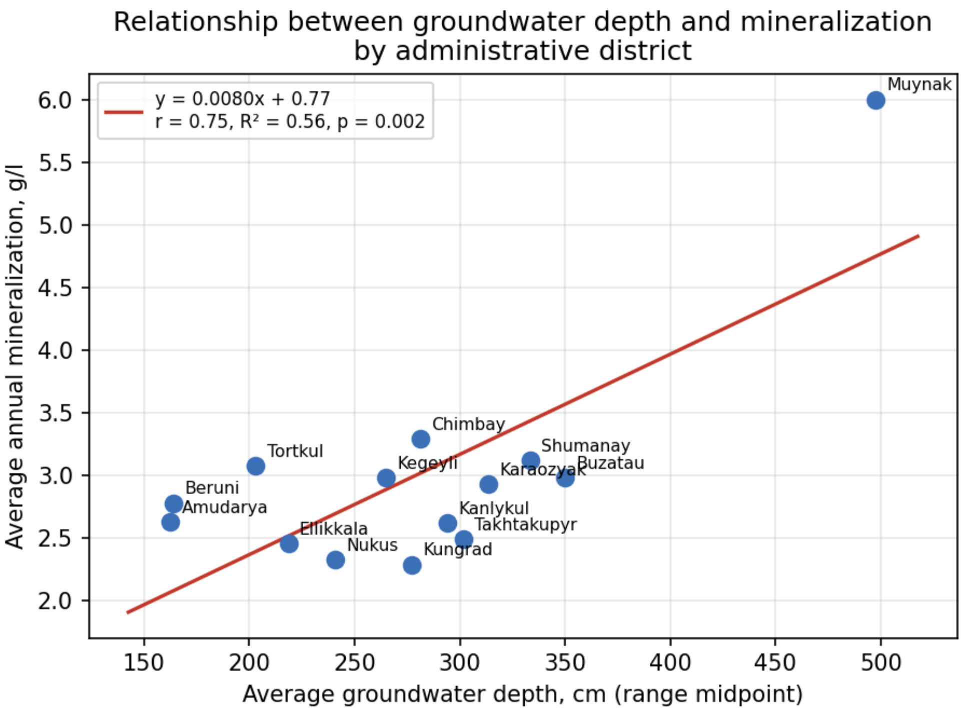

Figure 2. Relationship between average groundwater depth and average annual mineralization across administrative districts of the Republic of Karakalpakstan, with fitted linear regression

Recommended mineralization thresholds for irrigation water. According to the internationally recognized FAO classification of irrigation water quality [14], the salinity hazard of irrigation water is commonly classified by electrical conductivity (EC) and the approximately corresponding total dissolved solids (mineralization), as summarized in Table 3. Comparing these thresholds with the district-level data in Table 2 shows that average mineralization in most districts of the Republic of Karakalpakstan (2.3–3.3 g/l) falls within the range associated with severe restriction on use for salt-sensitive crops, while in Muynak district (6.0 g/l) mineralization exceeds the range generally considered usable even for tolerant crops without specific leaching and drainage management.

Table 3.

Classification of irrigation water salinity hazard (adapted from Ayers & Westcot, FAO Irrigation and Drainage Paper 29, 1985) [14]

Degree of restriction on use	EC, dS/m	Approx. mineralization, g/l
None	< 0.7	< 0.45
Slight to moderate	0.7 – 3.0	0.45 – 2.0
Severe	> 3.0	> 2.0

Comparison with other regional studies. The finding that groundwater mineralization of 1–3 g/l covers about 85 % of the irrigated area of the Republic of Karakalpakstan (439.7 of 515.3 thousand ha) is consistent with a recent basin-wide climate-risk assessment, which reported the same mineralization range covering more than 85 % of irrigated land across the entire Amu Darya river basin [16]. District-level studies in Khojeyli [5] and Amudarya [8] districts likewise report shallow, moderately to highly mineralized groundwater linked to irrigation return flow and insufficient drainage, corroborating the mechanisms described above. Long-term hydrological studies further indicate that the flow of the Amu Darya in its middle and lower reaches has declined markedly over recent decades, an effect attributed mainly to expanding upstream water withdrawals rather than to climate change alone [17]. A continued reduction in river discharge would be expected to reduce filtration recharge of the near-river groundwater flow described above, potentially weakening the natural freshening that currently keeps mineralization lowest along the river corridor; monitoring this relationship is recommended as a priority for future research.

Conclusion

On the irrigated area of 515.3 thousand hectares, groundwater at a depth of 0–1 m occupies 7.8 thousand ha; 1–1.5 m — 48.9 thousand ha; 1.5–2 m — 267.8 thousand ha; 2–3 m — 120.9 thousand ha; 3–5 m — 66.9 thousand ha; and more than 5 m — 2.25 thousand ha. Groundwater mineralization varies as follows: 0–1 g/l occupies 2.7 thousand ha (0.5 %); 1–3 g/l occupies 439.7 thousand ha (about 85 % of the irrigated area, consistent with recent basin-wide estimates); 3–5 g/l — 72.8 thousand ha (14.1 %); 5–10 g/l — 6.06 thousand ha (1.2 %); and more than 10 g/l — 0.3 thousand ha (0.1 %). A statistically significant positive relationship (Pearson $r = 0.75$, $R^2 = 0.56$, $p = 0.002$) between average groundwater depth and mineralization across districts confirms that deeper, poorly drained groundwater in the peripheral parts of the delta is associated with higher salt content.

The conducted analysis of hydrochemical data of groundwater over recent years shows that mineralization and the content of individual ions and microelements exceed the permissible levels according to the standards «Drinking Water» and «Water for Irrigation,» the list of maximum permissible concentrations (MPC) of the NIGMI Institute, and the classification of the Scientific-Research Institute of Irrigation and Water Problems. This leads to the violation of the hydroecological state of irrigated territories. Given the documented long-term decline in Amu Darya discharge in its middle and lower reaches over recent decades, mainly attributed to expanding upstream water use [17], continued hydrogeological and hydroecological monitoring, together with optimization of irrigation-drainage networks and reduction of water losses, is essential to prevent further degradation of irrigated land in the Republic of Karakalpakstan.

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Changes in hydrological regime and formation of peak water discharges in the Amudarya river delta

Kurbanbaev Sagit
PhD, Senior Researcher, Director
Karakalpak Branch of the Scientific Research Institute of Irrigation and Water Problems
Republic of Uzbekistan, Nukus
http://orcid.org/0000-0002-6772-7453
E-mail: kurbanbaev69@mail.ru

Kaipov Islam Perdebaevich
Assistant, Lecturer
Karakalpakstan Institute of Agriculture and Agrotechnology
Republic of Uzbekistan, Nukus

Изменения гидрологического режима и формирование пиковых расходов воды в дельте реки Амударья

Курбанбаев Сагит Ережепович
PhD
ст. науч. сотр., директор, Каракалпакский филиал Научно-исследовательского института ирригации и водных проблем
Республика Узбекистан, г. Нукус

Каипов Ислам Пердебаевич
ассистент
-преподаватель Каракалпакстанский институт сельского хозяйства и агротехнологий
Республика Узбекистан, г. Нукус

Abstract

The article gives an analysis of long-term (1965–2022) trends in the river flow regime of the Amudarya, peak discharges at the Kiziljar hydrological station (as an inflow to the three largest reservoirs in the Amudarya delta: Mezhdurechie, Moynaq, and Ribachie), and actual storage capacities of these reservoirs based on field GPS leveling data and ArcGIS bathymetric modeling. The Visual C# mathematical water balance model was used to explore the water resources of the

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investigated delta reservoirs under different inflow scenarios. It was found that the natural flow of the Amudarya was reduced by half in 1965–2006 (390 m3/s), with the peak outflow at Kiziljar being 714.1 m3/s (3 %-exceedance probability discharge). The water balance calculations for the 2010 wet, 2019 average, and 2001 dry years showed that Kiziljar reservoirs require a minimum annual inflow of 515.55 Mm3 to store water in all three reservoirs. The GPS survey leveling and ArcGIS slope analysis results indicated that the actual storage capacity of the Kiziljar reservoirs is 12–17.5 % below the designed capacity due to severe silting. At the same time, hydrobiological monitoring in 2022–2023 revealed a reduction in zooplankton species richness by 34 % (from 40 to 27 species) compared to previous studies: 15 species of Rotifera, 6 species of Cladocera, and 6 species of Copepoda. The obtained results can serve as the basis for developing a hydrological and water use management strategy for the Aralo-Caspian region with the changing flow of the Amudarya.

Аннотация

В статье проводится анализ долгосрочных (1965–2022) тенденций режима речного стока Амударьи, пиковых расходов на гидрологическом посту Кизилджар (как притока в три крупнейших водохранилища в дельте Амударьи: Междуречье, Мойнак и Рыбачье) и фактических емкостей этих водохранилищ на основе данных полевого GPS-нивелирования и батиметрического моделирования в ArcGIS. Для исследования водных ресурсов изучаемых дельтовых водохранилищ при различных сценариях поступления воды использовалась математическая модель водного баланса на Visual C#. Установлено, что естественный сток Амударьи сократился вдвое в период 1965–2006 гг. (390 $м^3/с$), при этом пиковый расход на посту Кизилджар составил 714,1 $м^3/с$ (расход при 3 %-ной вероятности превышения). Расчеты водного баланса для влажного 2010 г., среднего 2019 г. и сухого 2001 г. показали, что водохранилищам Кизилджара требуется минимальный годовой приток 515,55 млн $м^3$ для накопления воды во всех трех водохранилищах. Результаты GPS-нивелирования и анализа уклонов в ArcGIS указали, что фактическая емкость водохранилищ Кизилджара на 12–17,5 % ниже проектной емкости из-за сильного заиления. Одновременно гидробиологический мониторинг в 2022–2023 гг. выявил снижение видового богатства зоопланктона на 34 % (с 40 до 27 видов) по сравнению с предыдущими исследованиями: 15 видов Rotifera, 6 видов Cladocera и 6 видов Copepoda. Полученные результаты могут служить основой для разработки стратегии гидрологического и водохозяйственного управления Арало-Каспийского региона с учетом изменяющегося стока Амударьи.

Keywords: Amudarya delta, hydrological regime, peak water discharge, reservoir, water balance, GIS, zooplankton.

Ключевые слова: дельта Амударьи, гидрологический режим, пиковый расход воды, водохранилище, водный баланс, ГИС, зоопланктон.

1. Introduction

The rational use of water resources is one of the most pressing problems in Central Asia today. The natural flow of water in the Amudarya River has changed significantly in the last few decades due to the active use of water for irrigation and climate change [1, p. 156; 3]. In the 1960s, the Amudarya River flowing into the Aral Sea was reduced by more than half in its lower reaches [1, p. 156].

In the 1950s, more than 140 large lakes in the Amudarya delta, covering an area of about 600 km², were formed [7]. By 2022, the number of these lakes had decreased twice, the tugai forests ten times, and the reed beds – 40 to 50 times [8, p. 29]. As a result of the Aral Sea's catastrophic drying up, three reservoirs were built in the former bed of the Amudarya River in Karakalpakstan to ensure the water supply of the local population, fisheries, and ecosystems. The Mezhdurechie reservoir was commissioned in 1978; the Moynaq and Ribachie reservoirs – in 1974 [2, p. 153; 9].

At the same time, with the reduction of stream flow, there is a threat to the reservoirs' functioning: on the one hand, they cannot be filled with water during droughts, and on the other hand, peak flows of up to 3,530 m³/s threaten to destroy the dam structure (for example, in Kiziljar in July 1969) [4, p. 176; 9]. The dam of the Mezhdurechie reservoir is designed for a maximum flood of 59.00 m asl (57.30 m asl – designed level), which corresponds to a 3 % probability of exceeding [4, p. 176; 9]. This study examines the hydrological and ecological issues of the Amudarya delta reservoirs, which is of great importance for the Republic of Uzbekistan. Presidential Decree No. PD-5202 of July 29, 2021, designates the Aral Sea region as the "Ecological Innovation and Technology Zone." This decree allocated specific tasks to study and stabilize the delta water bodies (Paragraph 16). However, the existing knowledge about the studied reservoirs is limited to the results of previous studies [2, p. 153]. In particular, a long-term hydrological assessment of the Kiziljar flow gauging station (1965 – 2022) and a morphological description using modern surveying methods have not been performed. The current state of the zooplankton complex was last studied more than ten years ago [5].

The objective of this study is to assess the long-term trends in the flow of the Amudarya River, the morphological characteristics of the reservoirs, and the state of their ecosystems. In particular, the following tasks were set: 1) to analyze the trends in annual and peak flows of the Amudarya River for the period 1965 – 2022; 2) to determine the morphological characteristics of the reservoirs; 3) to simulate the water balance of the reservoirs for wet, average, and dry years; 4) to study the zooplankton complex as an indicator of the hydrological and ecological state of the reservoirs.

2. Materials and Methods

2.1. Study objects. The study was conducted on three reservoirs in the Central (Amudarya riparian) zone of the Amudarya delta in Karakalpakstan, Uzbekistan. The Mezhdurechie reservoir (17,863 ha, 191.0 M m³) is located in the inter-channel area between the Oqdarya and Qipchoqdarya distributaries and receives water from the Amudarya River through the Takhiatash hydraulic structures. The Moynaq reservoir (12,529 ha, 184.9 M m³) is fed by the Glavmyaso canal, while the Ribachie reservoir (6,243 ha, 124.9 M m³) is located in the former Saribas Bay and is supplied with water from the Marinkinyuzyak canal [9, 4].

The Kiziljar flow gauging station is located about 55 km downstream of the Takhiatash headworks and provides information on the flow of water entering the Mezhdurechie reservoir.

2. 2. Hydrological analysis. The streamflow data of the Amudarya River at the Kiziljar station for the period 1965 – 2022 (58 years) were used to analyze the long-term trends in the river flow. The exceedance probability curve was constructed using the Chegoday formula: $P = (m - 0.3) / (n + 0.4) \times 100$ %, where m is the rank, n is the number of observations. The following hydrological characteristics were calculated: the multi-year average discharge Q_0 (m^3/s), variation coefficient Cv, and the coefficient of skewness Cs [12].

2. 3. Morphometric surveys. In 2022 – 2023, the morphological characteristics of the reservoirs were studied using high-precision GPS leveling. The study involved dividing the reservoirs into transects (Mezhdurechie – 6 transects; Moynaq – 8 transects; Ribachie – 6 transects). In each transect, absolute heights and coordinates were measured, and an isobath map was made in ArcGIS 10.7 software. Using this map, the relationships between the reservoir's area and volume were determined as functions of the water level $\omega = f(H)$ and $V = f(H)$. The volume was calculated using the formula $V = \Sigma (W_i + W_{i+1}) / 2 \times \Delta h_i$, where W_i is the area at the i-th contour, and Δh_i is the interval between adjacent contours [6, 9].

2. 4. Mathematical water-balance modeling. A water balance model of the three-reservoir system was developed in the Visual C# programming language. The basic equation for calculating the change in storage for each reservoir is presented by the following differential equation: $dW_i/dt = Q_p - q_r - q_e - q\_f \pm q_o$, where Q_p is the inflow of water into the reservoir from the Amudarya River; q_r – channel losses; q_e – reservoir outflow due to evaporation; q_f – filtration losses; q_o – outflow of water through connecting structures or between reservoirs. To determine the input characteristics for the water balance model, the average monthly flow of the Amudarya River was used, measured at the Samanboy flow gauging station. For the calculations, three scenarios were used: a wet year (2010 – 16,817.7 M m³), an average year (2019 – 1,674.4 M m³), and a dry year (2001 – 100.9 M m³) [6].

2.5. Hydrobiological surveys. In 2022 and 2023, during the summer and autumn seasons, zooplankton surveys were carried out. In total, 32 samples were taken (23 – quantitative and 9 – qualitative) with a conical plankton net (mesh size – 76). Water was taken from the nets by passing 100 L of water through them or by towing. The samples were fixed in 2-3% formalin solution. Zooplankton was counted and identified using a binocular microscope. The results of the quantitative analysis were used to determine the number of individuals per cubic meter of water (ind./m³) and the biomass in milligrams per cubic meter (mg/m³) [10, 11]. Using the individual weight-length relationship, the biomass was calculated [16, p. 183].

3. Results and Discussion

3.1. Long-term dynamics of discharge at Kiziljar (1965 – 2022)

The analysis of the Kiziljar station data for the period 1965 – 2022 shows a long-term decline in the flow of the Amudarya River into the delta (Table 1). In particular, for the period 1965 – 2006, the average annual discharge decreased from 390 to 177.5 m³/s, and for the period 1980 – 2021 – from 350 to 177.5 m³/s. The absolute maximum monthly average flow was recorded in July 1969 and amounted to 3,530 m³/s. Since 1998, the flow has not been so high in the Amudarya River. At the same time, a decrease in flow below 50 m³/s was noted in 2001, 2006 – 2008, 2014, 2018, and 2021 (Figure 1).

Table 1.

Selected mean annual discharges and exceedance probabilities at Kiziljar gauging station, 1965–2022 [2, p. 153; 9]

Year	Mean Annual Flow, m³/s	Exceedance Probability, %
1965	1,038.0	1
1969 (max)	1,781.0	~1
1980	271.0	2
1988	516.6	9
1992	675.3	4
1998	714.1	2
2000	66.3	61
2001 (min)	2.8	98
2010	484.2	11
2019	39.0 (avg)	70
2022 (est.)	4.0	94

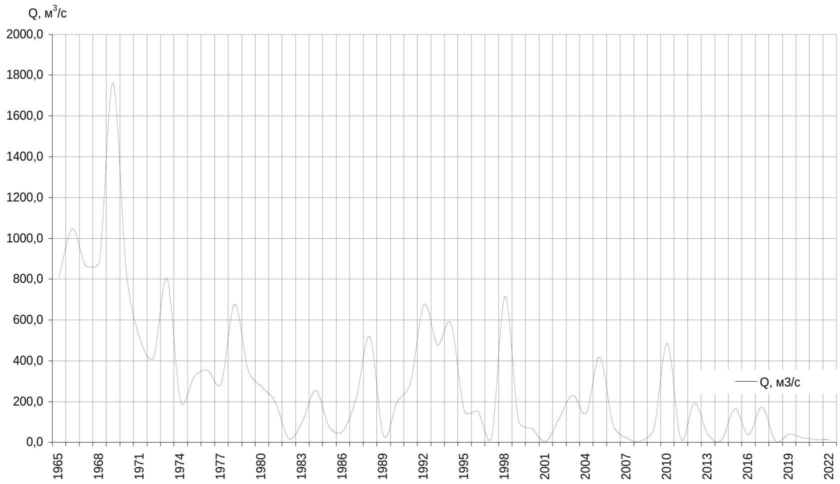

Figure 1. Annual mean discharge fluctuations at Kiziljar gauging station, 1965–2022

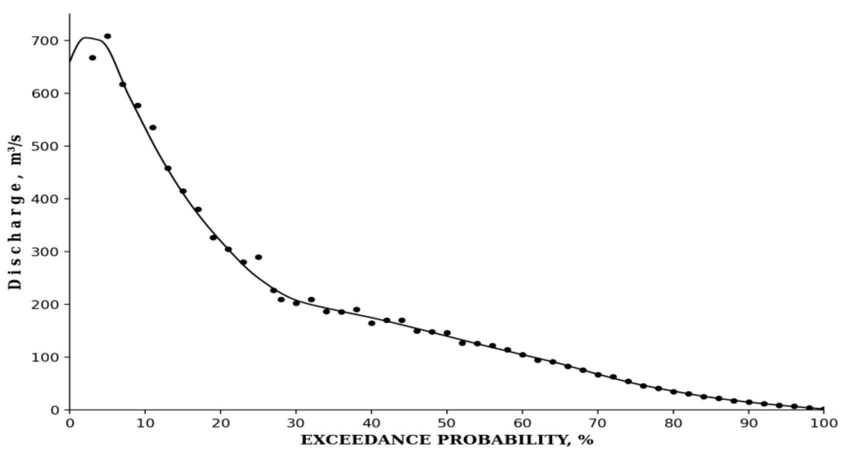

Figure 2. Exceedance probability curve at Kiziljar gauging station, 1980–2021

From the frequency curve (figure 2), the 3 % exceedanceprobability discharge, which is the design peak for Mezhdurechie dam, is equal to 714,1 m³/s. Optimisation of the joint operating regime of the Tuyamuyun reservoir and the Takhiatash headwork allows to reduce the peak of the flood wave transferred to the delta by 12 – 15 %. This confirms the calculations of Kurbanbaev [2, p. 153] performed on the data of the 2006 available up to the time of the study.

3.2. Actual morphometric characteristics of the reservoirs

Determination of actual morphometric characteristics of the reservoirs using GPS leveling and mathematical modeling in ArcGIS gave the results presented in Table 2. In all three reservoirs, the volumes accounted for less than the design ones: Mezhdurechie – 83 %, Moynaq – 88 %, Ribachie – 82,5 %. The reason for this is the silting of intake structures and shoaling of the reservoirs' bottom.

Table 2.

Actual and project morphometric characteristics of the Amudarya delta reservoirs (field surveys 2022-2023)

Reservoir	Actual Area (ha)	Design Area (ha)	Actual Volume (M m³)	Design Volume (M m³)	Mean Depth (m)
Mezhdurechie	17,863	21,436	191.0	230.0	≈2.5
Moynaq	12,529	15,034	184.9	210.0	1.48
Ribachie	6,243	7,304	124.9	151.4	2.0
Total	36,635	43,774	500.8	591.4	—

Bathymetric maps of the reservoirs are shown in Figs. 3–7. By comparing the isobathes of Mezhdurechie in 2002 (Fig. 3) and 2022 (Fig. 4), one can observe that the deep water areas are shifted to the south compared to the 2002 boundaries, especially in the west and south-west which is explained by the priority of the Oqdarya inflow with its suspended load. On the other hand, the areal – volume curves (Figs. 5,7,8) are used in the operational management of the reservoirs by the Department of Reservoir Regulation.

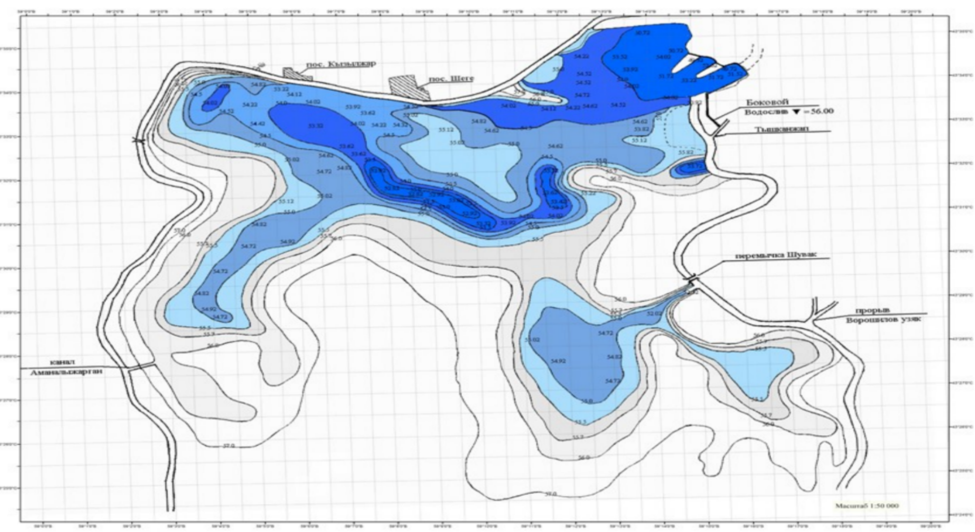

Figure 3. Isobath map of Mezhdurechie reservoir, 2002

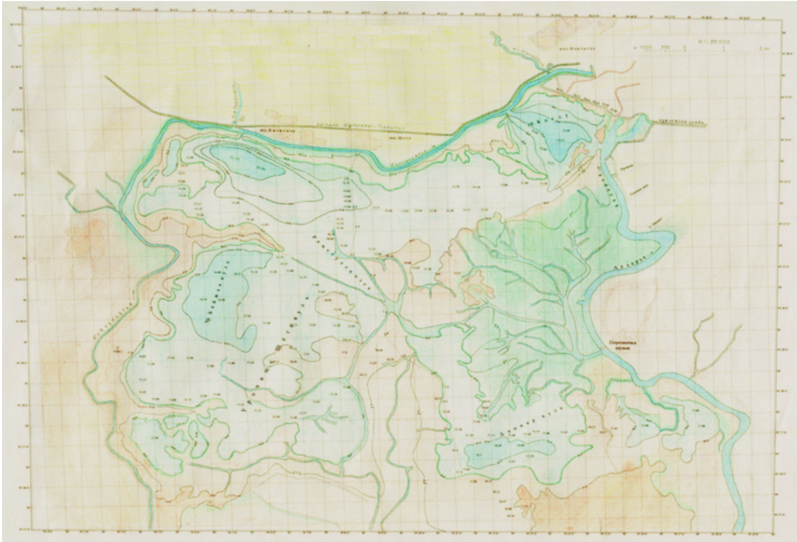

Figure 4. Isobath map of Mezhdurechie reservoir, 2022

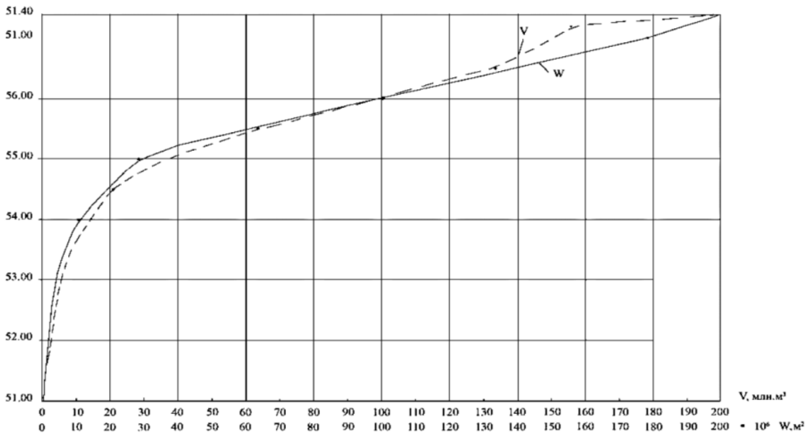

Figure 5. Area-volume bathymetric curves of Mezhdurechie reservoir: ω = f(H) and V = f(H)

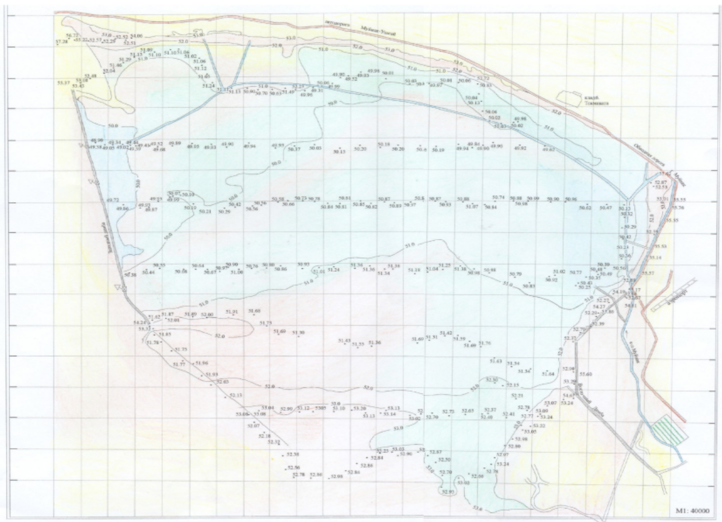

Figure 6. Depth isobath map of Moynaq reservoir, November 2023

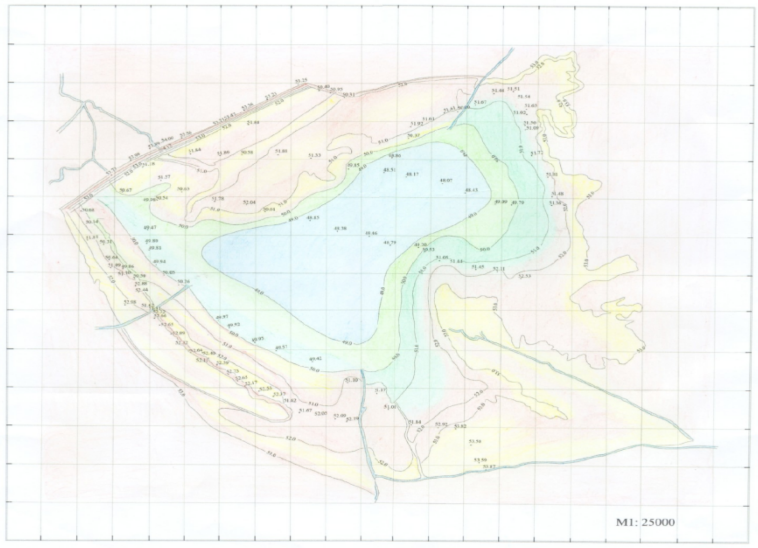

Figure 7. Isobath plan of Ribachie reservoir, January 2023

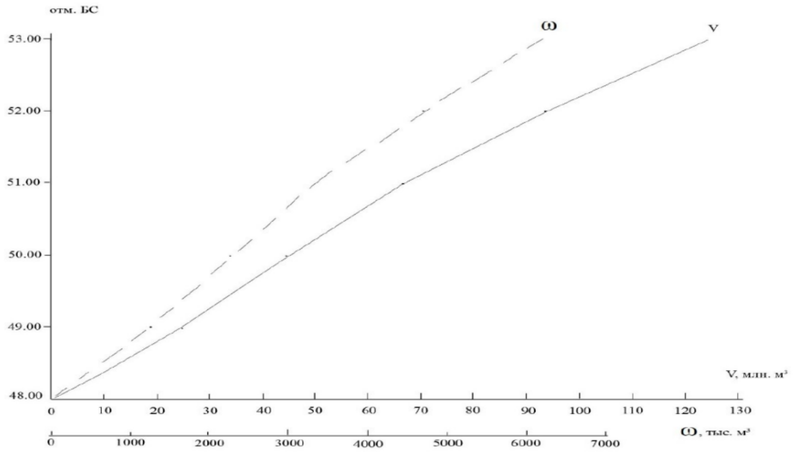

Figure 8. Area-volume bathymetric curves of Ribachie reservoir: ω = f(H) and V = f(H)

3.3. Water-balance simulation results

The results for the chosen three years are summarised in Table 3. It can be seen that the total amount of inflows for the wet year of 2010 accounted for 16,817.7 M m^3, which significantly exceeded the reservoirs' total storage capacity of 499.9 M m^3. This means that about 12,214.9 M m^3 (or 72.7%) of the total inflows have been diverted to the former Aral Sea bed (a draught region), which is a major concern for the water-resources management in the basin. On the contrary, in the average year of 2019, the total inflows only amounted to 1,674.4 M m^3, which was enough to fill all the three reservoires to the brim with a remaining 852.4 M m^3 (50.9%) spilled away downstream. Finally, in the dry year of 2001, the inflows were only 100.9 M m^3 as compared to the needed minimum of 515.55 M m^3, which caused a deficit of 399.1 M m^3.

Table 3.

Water-balance components of the Amudarya riparian zone for the three years

Component	Wet year 2010	Average year 2019	Dry year 2001
Annual inflow volume, M m^3	16,817.7	1,674.4	100.9
Channel transmission losses, M m^3	4,204.4	418.6	25.2
Useful reservoir storage (3 res.), M m^3	499.9	499.9	184.2

Component	Wet year 2010	Average year 2019	Dry year 2001
Total evaporation, M m³	287.1	100.4	4.95
Discharge to former Aral Sea bed, M m³	12,214.9	852.4	0.0
Required optimal annual inflow, M m³	—	—	515.6 (norm)

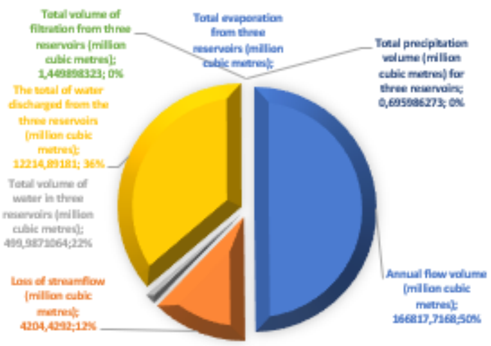

Figure 9. Proportional water-balance components under wet-year conditions (2010)

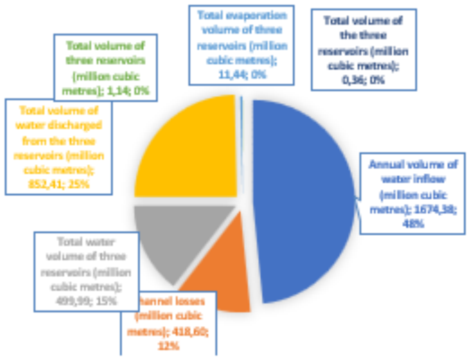

Figure 10. Proportional water-balance components under average-year conditions (2019)

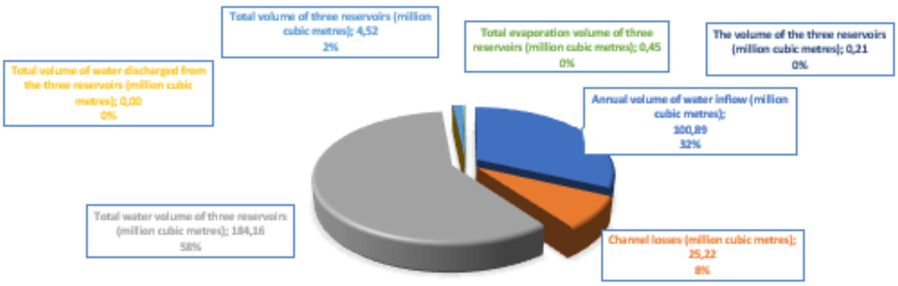

Figure 11. Proportions of water-balance components for a dry year (2001)

The obtained results have particular importance in terms of engineering infrastructure. Thus, the complete restoration of the Glavmyaso canal (15 – 20 m^3/s instead of 44 m^3/s in the project) and the Marinkinyuzyak canal (20 instead of 50) will increase the overall storage capacity by 669.5 million m^3 (reaching 1169.5 million m^3 in total). This will significantly alleviate the problem of outflows even in the case of a wet year [4, p. 176; 9].

By comparing the obtained results with similar research presented by Kurbanbaev [2, p. 153], one can notice that the amount of freshwater outflows decreased by more than half, and the number of years with extremely low outflow rates significantly increased. In other words, the results confirm the validity of the norms adopted in the abovementioned study, which are now used to process 16 years of hydrological data instead of 6.

3.4. Zooplankton biodiversity as a hydrobiological indicator

In total, 27 species of zooplankton were identified in the waters of the three reservoirs during the 2022/2023 survey expeditions (Table 4). Among them, 15 species (55.6 %) belong to the class Rotifera, 6 species (22.2 %) – to the class Cladocera, and 6 species (22.2 %) – to the class

Copepoda. Notably, 7 species of zooplankton were found for the first time in the waters of the lower Amudarya: Hexartra mira, Asplanchna sieboldi, Polyarthra vulgaris, Bdelloida gen. sp., and others.

Table 4.

Zooplankton biodiversity in the delta reservoirs of the Amudarya River (2022-2023)

Taxonomic group	No. of species	Mezhdurechie share, %	Ribachie share, %	Moynaq share, %
Rotifera	15 (56%)	57–88	60	70
Cladocera	6 (22%)	22	20	16
Copepoda	6 (22%)	21–45	20	14
Total	27	100	100	100

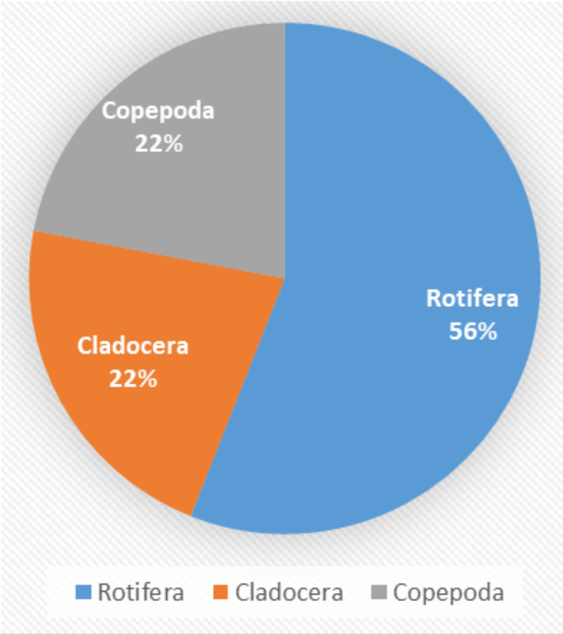

Figure 12. Proportion of the main zooplankton taxonomic groups in the studied reservoirs

The species richness was found to decrease by 34 % compared to the 2003 – 2004 baseline (41 species) [17, p.10] and by 25 % compared to the 1968 – 1983 baseline (36 species, excluding Rotifera) [5, p.585]. The strongest deviation was observed in the Ribachie and Moynaq reservoires, where salinity increased to 1.5 – 4.0g/L, resulting in proliferation of salt-adapted rotifers (up to 70,000 ind./m^3 in Moynaq reservoir in summer 2023) and a decrease in the number of freshwater stenohaline species. The absolute biomass of zooplankton reached the maximum in the Mezhdurechie reservoir (4,400 mg/m^3 in August), which may be associated with more predictable hydrological regime [18].

This trend of community simplification and replacement of freshwater specialist species by generalists tolerant to increased salinity can be regarded as typical for the remnants of the former Aral Sea [13, p.83; 14]. Its detection in the study area qualifies as an early warning signal of impending changes in water quality. Therefore, it is advisable to conduct hydrobiological monitoring of the reservoirs as a part of the measures stipulated by the President of Uzbekstan in PD-5202.

4. Conclusions

1. The longest available series of flow observations at the Kiziljar gauging station has enabled to reveal a negative long-term trend in the annual discharge. The multi-year mean seasonal discharge decreased from 390 m^3/s (1965 – 2006) to 177.5 m^3/s (1980 – 2021). The design discharge of the structures in the study area, corresponding to a frequency of 3 %, equals 714.1 m^3/s. The optimization of Tuyamuyun reservoir's operating rules can allow to reduce the maximum transmission by 12 – 15 %.

2. The geodetic GPS and ArcGIS surveys have determined the actual morphometric characteristics of the reservoirs: Mezhdurechie – 17,863 ha / 191.0 Mm^3; Moynaq – 12,529 ha / 184.9 Mm^3; Ribachie – 6,243 ha / 124.9 Mm^3. All the three reservoirs were found to be 12 – 17.5 % lower than their design capacity due to the degradation of the irrigation canals.

3. The water balance computations showed that: (a) under wet-year scenario, 72.7 % of the inflow to the former Aral Sea area is unutilized and thus can be used to fill the reservoirs; (b) under dry-year scenario, the deficit of water compared to the minimum required for the reservoir's operation constitutes 399.1 Mm^3; (c) the minimum annual inflow necessary for the reservoir operation equals 515.55 Mm^3; (d) the reconstruction of the canals will allow to increase the total storage capacity by 1,169.5 Mm^3.

4. In the zooplankton survey, 27 species were identified, which is 34 % lower than in 2003 – 2004. An increase in the salinity level in the Ribachie and Moynaq reservoirs was found to lead to community homogenization with the development of advective-dominant water regime and proliferation of halophilic species. It can be concluded that the ecological status of the reservoirs is moderate, requiring coordinated management and optimization measures.

5. Practical recommendations: (i) reconstruct the Glavmyaso canal to design capacity (44 m^3/s) and the Marinkinyuzyak canal (50 m^3/s); (ii) implement coordinated joint dispatch of Takhiatash headwork and Tuyamuyun reservoir; (iii) establish routine hydrobiological monitoring at all three reservoirs as required by the Presidential Decree of the Republic of Uzbekistan No. PD-5202 [3].

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