



Dynamics of Hydrogeochemical Infiltration During Artificial Groundwater Recharge in Daily Regulation Basins: A Case Study of the Lepsinsky Experimental Site

Aida Ismagulova,¹ Vitaly Kulagin,² Adiya Zhumabek,² Nurbol Itemen,² Nurbol Tileuberdi,^{2,*} Ahmed N. Al-Dujaili³ and Aigul Issagaliyeva⁴

Abstract

This study explores sustainable groundwater management in semi-arid southeastern Kazakhstan, focusing on the feasibility of managed aquifer recharge (MAR) at the Lepsinsky experimental site in the Almaty Region. With surface water resources declining due to climate change and human activity, MAR presents a promising solution for water-scarce areas. Researchers constructed an infiltration trench 650 meters from the Lepsy River and established a temporary hydrological monitoring station to assess infiltration dynamics and colmatation processes. Hydrogeological assessments included lithological analysis, infiltration testing, and turbidity monitoring. Results indicated favorable infiltration conditions, with filtration coefficients ranging from 0.11 to 4.32 m/day depending on sediment composition. Volumetric moisture tracking showed full saturation within 50–72 hours, confirming effective percolation. Turbidity levels remained acceptable, and portable turbidity meters closely aligned with standard methods ($R = 0.90$). The findings support MAR implementation at the Lepsinsky site, particularly for decentralized rural and agricultural water supply systems. The study offers a replicable framework for designing and optimizing recharge systems in similar environments, contributing to future groundwater sustainability and infrastructure planning in arid regions.

Keywords: Groundwater reserves; Infiltration basin; physical model; Volumetric humidity; Hydrogeochemistry.

Received: 02 May 2025; Revised: 02 June 2025; Accepted: 10 June 2025.

Article type: Research article.

1. Introduction

Groundwater is an overwhelmingly valuable source, while its limited proportion and quality are of international concern.^[1] Groundwater is an essential water resource of up to 99% of the international freshwater resources and is used for nearly 50% of the drinking water output, 50% of the river stream supply, and assists about 40% of food production worldwide.^[2] Artificial groundwater refill is a comparatively economical

and active method for resolving insufficiency and disparate locative-interim division of water resources.^[3] Variations in groundwater quality over the refill process are a consideration that should be classified.^[4] Identifying the hydrogeochemical reactions that occur during recharge can be vital in predicting trends in groundwater quality.^[5]

Recent peer-reviewed studies published in Scopus- and Web of Science-indexed journals highlight the growing global reliance on Managed Aquifer Recharge (MAR) as a strategic response to declining surface water availability and aquifer depletion.^[4] For instance,^[6] present an overview of emerging MAR technologies and their potential for sustainable groundwater governance, while explore how climate-induced changes influence groundwater quality.^[2] demonstrate the use of geospatial tools to identify optimal recharge zones in semi-arid regions. These contemporary contributions underscore the relevance of MAR for regions like southeastern Kazakhstan, where climatic and anthropogenic pressures necessitate resilient groundwater solutions.

Riverbank regions and shallow inflow systems are natural

¹ Institute of Hydrogeology and Geoecology LLP, Almaty, 050010, Kazakhstan

² Department of Hydrogeology, Engineering and Petroleum Geology, Satbayev University, Almaty, 050000, Kazakhstan

³ Petroleum Engineering Department, Amirkabir University of Technology, No. 350, Hafez Ave, Valiasr Square, Tehran, 1591634311, Iran

⁴ Department of Geophysics and Seismology, Satbayev University, Almaty, 050000, Kazakhstan

*Email: n.tileuberdi@satbayev.university, 1983nureke@gmail.com (N. Tileuberdi)

adsorption and disintegration barricades that could eliminate pollutants, organic substances, and pathogens from recharge water effectively.^[7] Water quality (WQ) is constantly an essential issue in the artificial groundwater recharge process.^[8,9] For artificial groundwater well recharge, WQ alterations are fundamentally controlled by physical blending between the recharge water and groundwater during the entire refill process, and are especially intense in the early procedures.^[10,11]

One of the most promising approaches to addressing this challenge is the implementation of Managed Aquifer Recharge (MAR) systems, which utilize controlled infiltration of surface water to stabilize and restore groundwater levels.^[12,13] One of the most functional planning tools for remedying groundwater depletion and boosting sustainable water management is Managed Aquifer Recharge (MAR).^[14] This practice involves the strategic water recharging to supplement the subsurface aquifer, which is the main goal of this method.^[15] The MAR efficiency reflects the ability to improve water quality and minimize electrical conductivity and total resolved particles, under the condition that the original water is pure and effectively managed siltation (Fig. 1).^[16]

The increasing scarcity of surface water resources in semi-arid regions of Kazakhstan—aggravated by climate change and intensified anthropogenic pressures—has elevated the strategic importance of sustainable groundwater management.^[17–20] The Lepsy River is one of the most water-abundant in the region and flows into the eastern part of Lake Balkhash.^[21–23] The total area of the site is 144.75 km², geologically characterized by Upper Quaternary alluvial and lacustrine-alluvial deposits. These conditions make it a favorable candidate for the development of decentralized potable water supply systems for rural settlements, livestock farms, and improved pastureland irrigation.^[24] To simulate seasonal infiltration under MAR schemes, a dedicated test trench was constructed 650 meters from the riverbank. This trench allowed for controlled experiments assessing

infiltration rates, specific yield, and the formation of colmatation layers. A temporary hydrological monitoring station was also installed to gather in-situ water quality data at the most suitable point for MAR system planning.^[25] The geomorphological and hydrogeological boundaries of the study site are clearly defined: the northern boundary corresponds to the watershed of the Lepsy River's left-bank floodplain, the southern boundary aligns with productive aquifers, the eastern boundary is marked by the Lepsy–Miyaly railway embankment (an anthropogenic hydraulic barrier), and the western boundary transitions into an aeolian-dominated ridge landscape.^[26–29]

The Lepsy River originates in the Dzungarian Alatau glaciers, at elevations exceeding 3,000 meters, and exhibits a distinct spring-summer high-flow regime driven by snowmelt and glacial discharge. Within the experimental section, the river displays a lowland, meandering profile, with an average width of 45–50 meters, hydraulic gradient of 0.0003, and variable water depths ranging from 0.5 to 1.5 meters depending on seasonal flow conditions.^[30–33] A key objective of this research was to assess turbidity levels—used as an indicator of suspended sediment content—which are critical for evaluating infiltration performance and the development of clogging (colmatation) in the infiltration media. For this purpose, advanced photometric methods using portable turbidity meters were deployed and validated against traditional gravimetric analyses, producing high-resolution and reliable data.^[34,35]

In summary, this study investigates the feasibility of such systems at the Lepsinsky experimental site, situated on the left bank of the midstream course of the Lepsy River in the Sarkand district of Almaty Region, southeastern Kazakhstan and to advance scientific understanding and practical design strategies for MAR systems in data-scarce, water-stressed environments. The focus is placed on integrating infiltration modeling, field experimentation, and real-time monitoring to inform the development of groundwater recharge infrastructure under semi-arid climatic conditions.

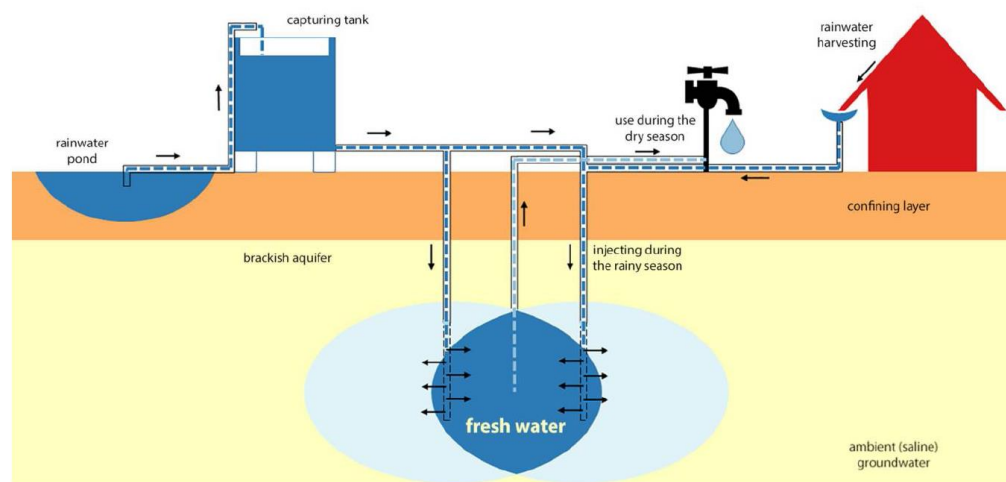


Fig. 1: Overview conceptualization of a managed aquifer recharge (MAR) system via basin. Reproduced with permission.^[16] Copyright © 2019 MDPI.

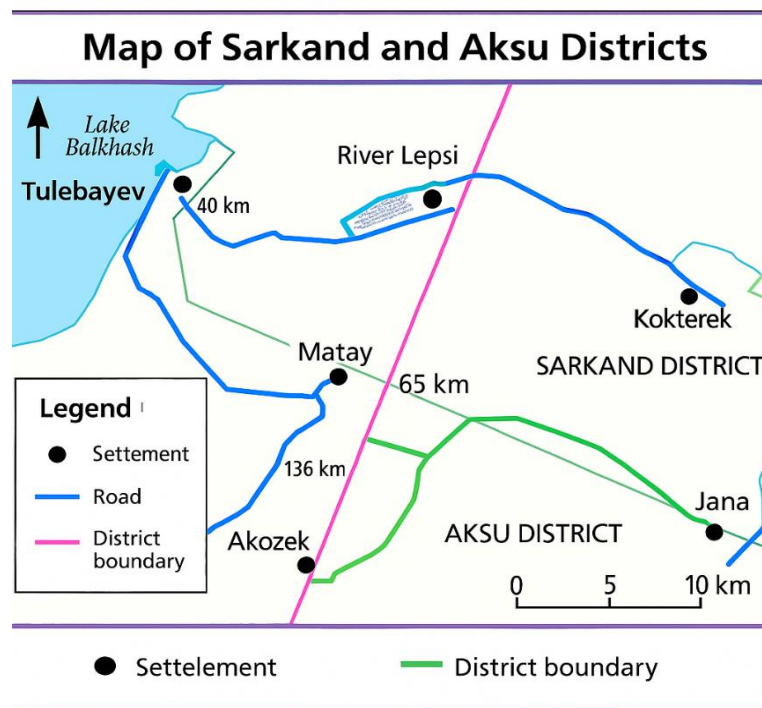


Fig. 2: Overview map of the Lepsinsky experimental site for scientific research on colmatation processes.

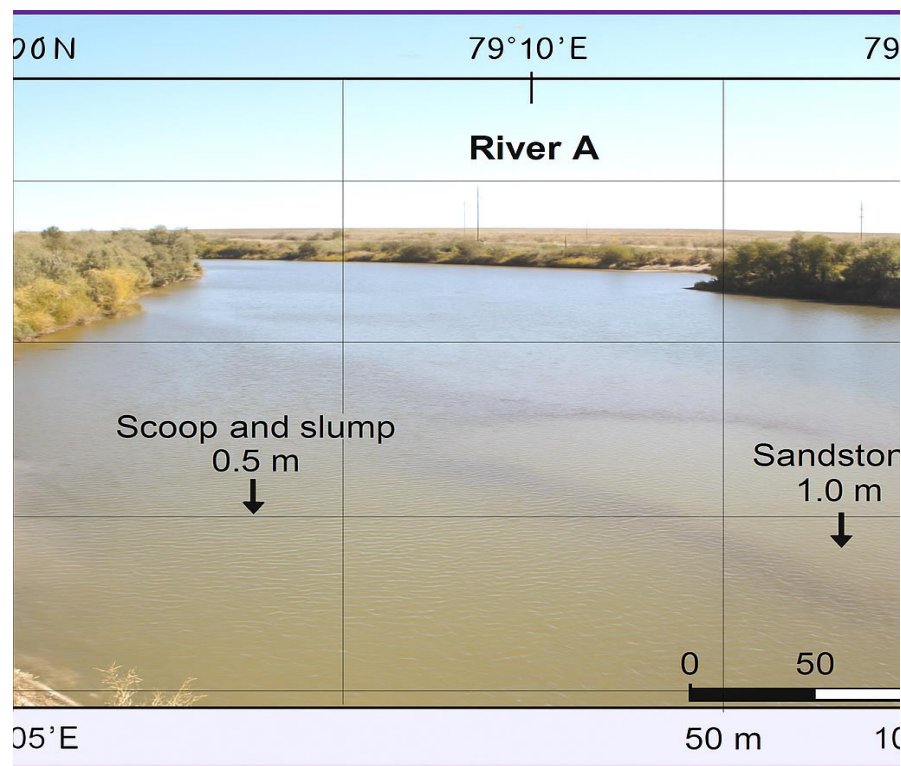


Fig. 3: Lepsy River within the boundaries of the experimental research zone.

2. Materials and methods

2.1 Site characterization and experimental design

The research was carried out at the Lepsinsky experimental site in the Sarkand district of the Almaty Region. The site lies on the left bank of the midstream course of the Lepsy River and encompasses 144.75 km² of Quaternary alluvial and

lacustrine-alluvial deposits. A test trench was constructed 650 meters from the riverbank to emulate the functionality of a seasonal infiltration basin under MAR schemes.^[19] In parallel, a temporary hydrological monitoring station was installed to assess baseline river water quality and its variation during recharge periods.^[36]

Fig. 2 presents a topographic overview of the Lepsinsky site in the Sarkand district, showing the location of the infiltration trench, hydrological monitoring station, and surrounding geomorphological boundaries. The map outlines key features including the Lepsy River channel, floodplain terraces, railway embankment, and aeolian formations, providing spatial context for subsequent experimental procedures.^[37] A field photograph illustrating the physical appearance of the Lepsy River at the selected study reach. The image captures the river's meandering form, riparian vegetation, and channel morphology, highlighting its lowland hydrological characteristics and suitability for MAR intake.

A field photograph illustrating the physical appearance of the Lepsy River at the selected study reach (Fig. 3). The image captures the river's meandering form, riparian vegetation, and channel morphology, highlighting its lowland hydrological characteristics and suitability for MAR intake.

2.2 Lithological profiling and soil sampling

A key component of the study involved detailed lithological profiling through excavation of a primary shaft (Shaft No. 5), reaching a depth of 3.9 meters. Stratigraphy revealed alternating layers of micaceous sands, silty loams, clays, and gravelly sands. Intact core samples were extracted and analyzed to determine bulk density, natural moisture content, and molecular moisture capacity. Grain-size distribution was assessed through sieve analysis, sedimentation, pipette, and hydrometer techniques in accordance with ISO and GOST standards.^[18,19] All laboratory procedures involving chemical

reagents and suspensions adhered to established environmental and safety protocols, including compliance with REACH regulations, GOST safety requirements, and API RP standards where applicable. Proper handling, labeling, and disposal of substances were ensured throughout the analytical process to minimize environmental impact and align with international best practices in hydrogeological research.

The effective grain diameter (d_{10}), a critical parameter for estimating colmatation potential, was calculated from cumulative particle-size distribution curves.^[38,39] Fig. 4 illustrates the grain-size distribution of sediments sampled from the main infiltration shaft. The curve indicates a range of textures from coarse sands to silty loams, with effective grain diameter (d_{10}) used to assess filtration capacity and susceptibility to colmatation. This parameter is crucial for predicting clogging behavior in infiltration structures.

2.3 Infiltration testing and filtration coefficient assessment

Infiltration capacity was assessed via two approaches: Direct infiltration into the experimental shaft and controlled recharge through miniature infiltration basins equipped with regulated intake systems.^[40,41] Water was delivered using a calibrated 2 m³ tank with a float-controlled valve and volumetric flowmeter, replenished by a 3 m³ tanker truck. Filtration discharge (Q) was calculated using a physical infiltration equation involving wetted depth (Z), capillary pressure ($H_{\text{с}}$), cross-sectional area (W), and water column height (h). Depending on the sediment type, the Nesterov method was used for clayey soils,^[22,42] and the Bol'dyrev method for sandy

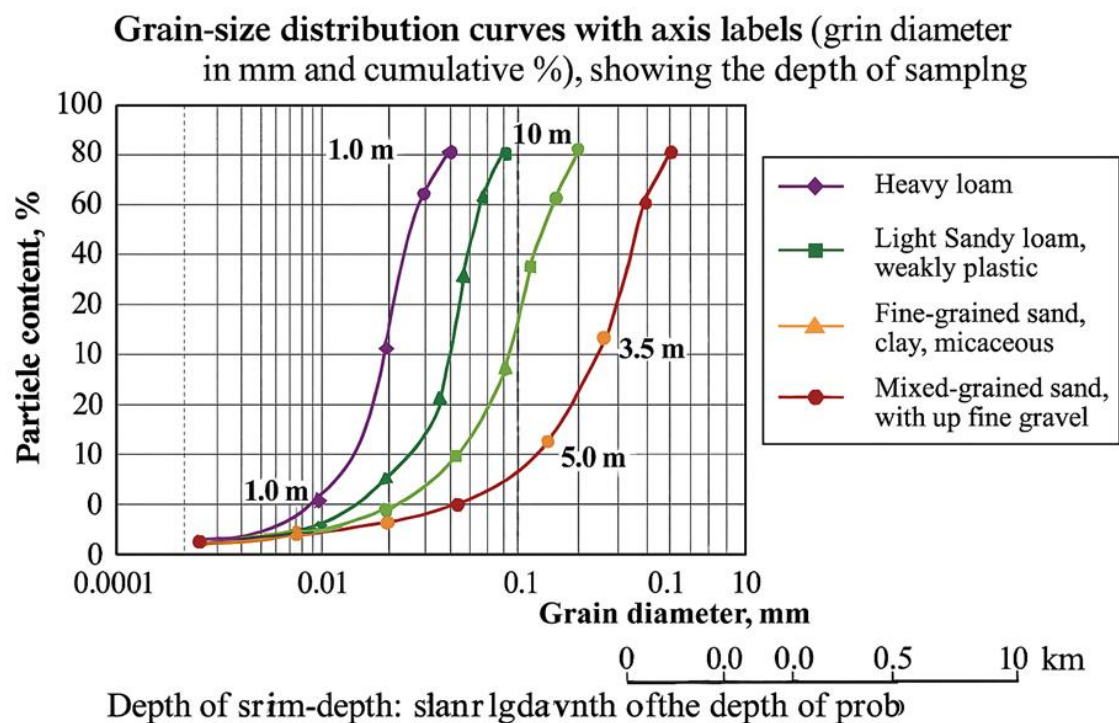


Fig. 4: Cumulative grain-size distribution curve of the cover deposits at the Lepsinsky site.

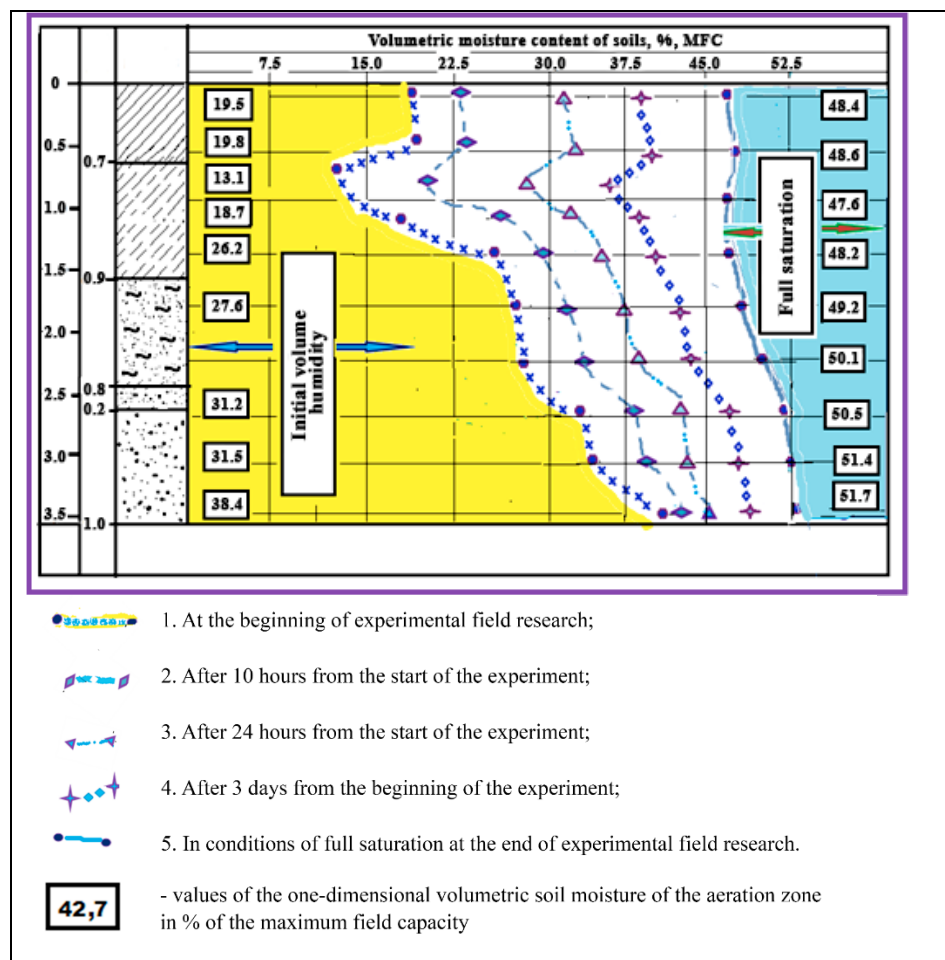


Fig. 5: Profiles and chrono-isopleths of volumetric soil moisture in the vadose zone.

soils. Field data were used to generate infiltration curves and chrono-isopleths of volumetric moisture distribution Eq. (1).^[25,43-47]

$$K = \frac{Q_x Z}{W_x (H_k + Z + h)} \quad (1)$$

where, Q - filtration discharge, m^3/day ; Z - depth of wetting after the experiment, m ; H_k - capillary pressure head, m ; W - filtration cross-sectional area, m^2 ; h - water column height in the ring (sump), m .

For low-permeability soils (e.g., clay), the Nesterov method was used;^[48] for permeable soils (e.g., sands), the Bol'dyrev method was applied.^[49]

To ensure the appropriate application of infiltration estimation techniques, the Nesterov method was specifically applied to low-permeability horizons consisting of compact clay and loam, as identified in Shaft No. 5, while the Bol'dyrev method was utilized for coarse-textured and well-drained sandy layers. This methodological distinction was based on the stratigraphic data, which detailed the vertical distribution of micaceous sands, silty loams, and clays. The integration of lithological profiles with corresponding infiltration methods ensures methodological consistency and enhances the reliability of the derived filtration coefficients. The results were summarized and presented as infiltration curves and moisture chronoisopleths.

2.4 Volumetric moisture tracking

Moisture content within the vadose zone was measured using intact soil cores collected at multiple time intervals: before infiltration, after 10, 24, 48, and 72 hours, and at full saturation (50–72 hours). Chrono-isopleth profiles visualized the progressive infiltration front across different depths and soil types, indicating effective water migration and saturation patterns. Fig. 5 shows a time-series contour visualization of volumetric moisture content within the unsaturated zone at different depths and durations (from 10 to 72 hours). It reflects the vertical movement of infiltrated water over time and highlights the saturation front progression, providing evidence of efficient percolation through variably permeable layers.

Further calibration was performed in the laboratory using a spectrophotometer at 530 nm. Standard kaolin suspensions ranging from 0.5 to 5.0 mg/L were prepared. The relationship between optical density and concentration was plotted (Fig. 6), and the resulting linear calibration curve conformed to the Beer–Lambert Law (Eq. (2)).^[50]

$$A = \varepsilon \times C \times J \quad (2)$$

where, A – optical density; ε – molar extinction coefficient; C – molar concentration of solution, mol/l ; J – cuvette thickness, cm .

The correlation coefficient between photometric and gravimetric results reached $R = 0.90$, indicating high

reliability of express turbidity measurements under field conditions. Fig. 6 demonstrates the relationship between optical density readings (using spectrophotometry at 530 nm) and known turbidity concentrations. The resulting linear curve validates the application of Beer–Lambert law and confirms the reliability of photometric methods for field estimation of suspended sediment concentrations in recharge water.

2.5 Turbidity monitoring and photometric calibration

Turbidity was measured using a Turb 350 IR WTW portable turbidimeter, offering high sensitivity across 0–1000 NTU. (Nephelometric Turbidity Units, NTU — a standard unit used to quantify turbidity based on the amount of light scattered by suspended particles in water). Measurements followed

Russian standard RD 52.08.104–2002.^[24] Calibration against kaolin suspensions was performed using GOST 3351–74,^[25] with additional validation via gravimetric methods conducted in a field laboratory (Fig. 7). To confirm photometric accuracy, lab-based spectrophotometry at 530 nm was employed, producing a Beer–Lambert-compliant calibration curve. The correlation coefficient ($R = 0.90$) demonstrated strong alignment between field and laboratory turbidity measurements. This correlation graph compares turbidity values obtained with the Turb 350 IR WTW turbidimeter against traditional gravimetric analysis under average flow conditions. A strong linear correlation ($R = 0.90$) demonstrates high accuracy and field applicability of portable instruments for rapid turbidity assessment during MAR operations.

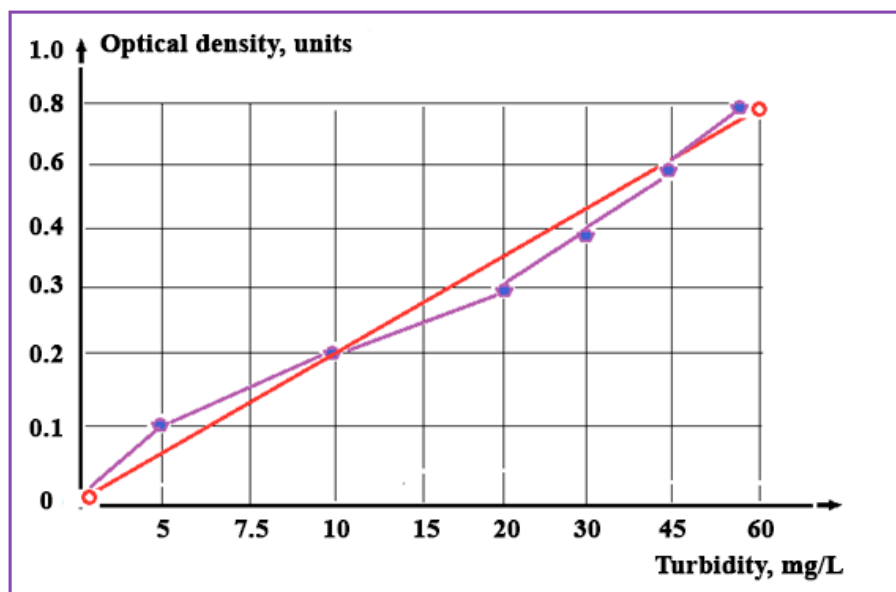


Fig. 6: Calibration graph of optical density versus turbidity based on standard kaolin suspensions.

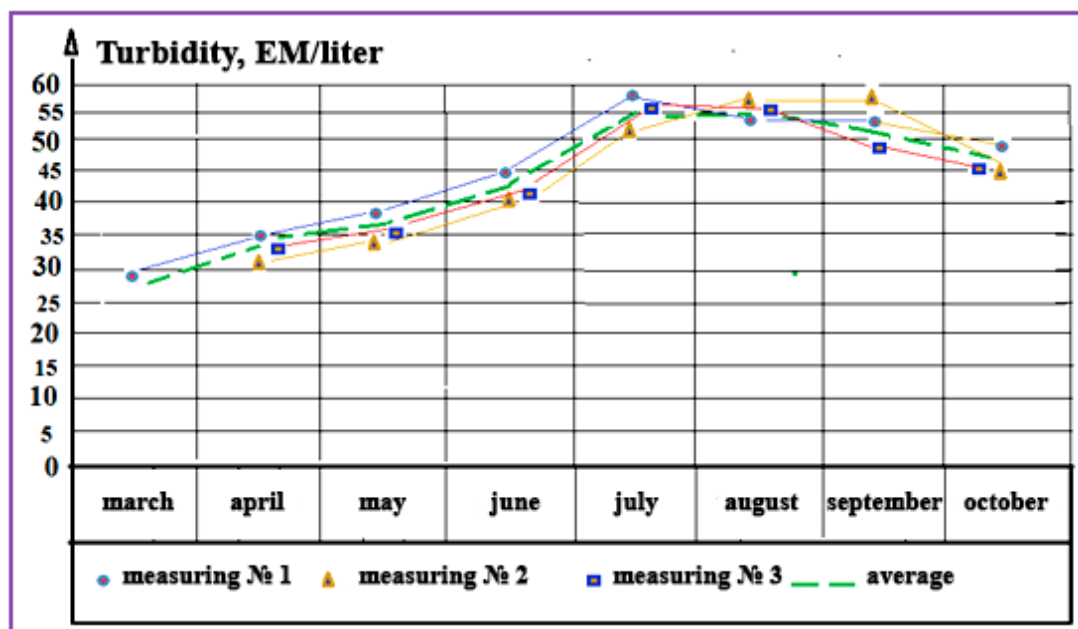


Fig. 7: Correlation of field-measured turbidity values of Lepsy River water using portable and gravimetric methods.

2.6 Summary of applied techniques

The integrated methodological framework provided: 1. High-resolution lithological and granulometric data; 2. Accurate filtration coefficients for varied sediment types; 3. Chrono-isopleths of water content within the vadose zone; 4. Reliable, real-time turbidity profiles with validated precision. These methods collectively support the feasibility evaluation and system design optimization for MAR applications in arid and semi-arid environments.

The application of this comprehensive methodological framework enabled the acquisition of high-resolution lithological, hydrodynamic, and water quality data under field conditions. These methods were specifically selected to evaluate the suitability of the experimental site for managed aquifer recharge and to characterize the dynamics of infiltration and clogging. The following section presents the results obtained from these investigations, providing empirical evidence on the hydrogeological behavior and recharge efficiency of the system.

3. Results and discussion

3.1 Results

The field investigations at the Lepsinsky experimental site yielded a comprehensive dataset characterizing the lithological structure, hydrogeological conditions, infiltration capacity, and water turbidity dynamics under managed aquifer recharge (MAR) scenarios. The study shaft (Sh-5) revealed a stratified profile consisting of fine-grained micaceous sands, silty loams, compact clays, and mixed gravely sands. Grain-size analyses conducted by sieve and pipette methods showed a dominance of fractions within 0.05–0.25 mm and notable presence of fine particles (<0.005 mm) in clay-rich horizons. Effective grain diameters (d_{10}) were derived from cumulative grain-size curves, providing input for filtration and clogging potential assessment.

Infiltration experiments using surface ponding in test shafts and miniature infiltration basins provided empirical values for the filtration coefficient (k_f). According to field data (Table 1), k_f ranged from 3.13 to 4.32 m/day for coarse-

Table 1: Comparative data of the values of filtration coefficients based on the results of filling and calculations at the Lepsinsky experimental site using the empirical formula of Hazen.

Lithological Composition of Sediments	Filtration coefficient, m/day		Absolute difference	difference %
	Filtration coefficient, m/day	Calculated values show		
Poorly sorted sand with up to 30% fine gravel	3.13	3.50	-0.37	-11.8
	4.32	4.05	+0.73	+6.6
Medium-grained sand	1.49	1.71	- 0.22	-14.7
	1.64	1.85	- 0.21	-12.8
Fine-grained sand	1.32	1.46	-0.14	-10.6
	1.38	1.33	+0.05	+3.8
Poorly sorted sand with interbedded lenses of medium loam	0.93	0.88	+0.05	+5.7
	1.10	1.06	+0.04	+3.8
Sandy loam	1.18	1.12	+0.06	+5.4
	0.79	0.75	+0.04	+5.3
Loam with interbedded lenses of medium-grained sand	0.71	0.73	-0.02	- 2.8
Heavy loam	0.11	0.12	+0.01	-1.1

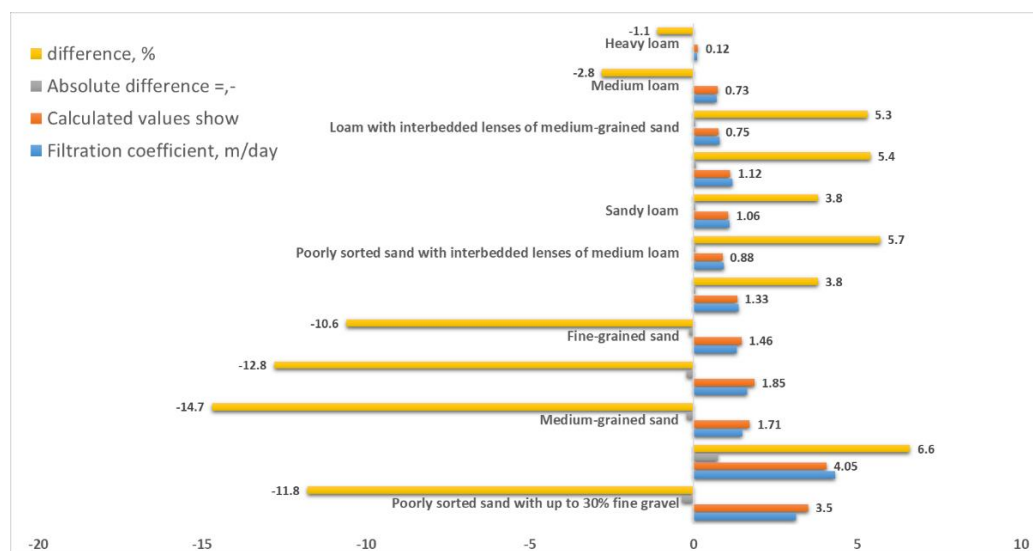
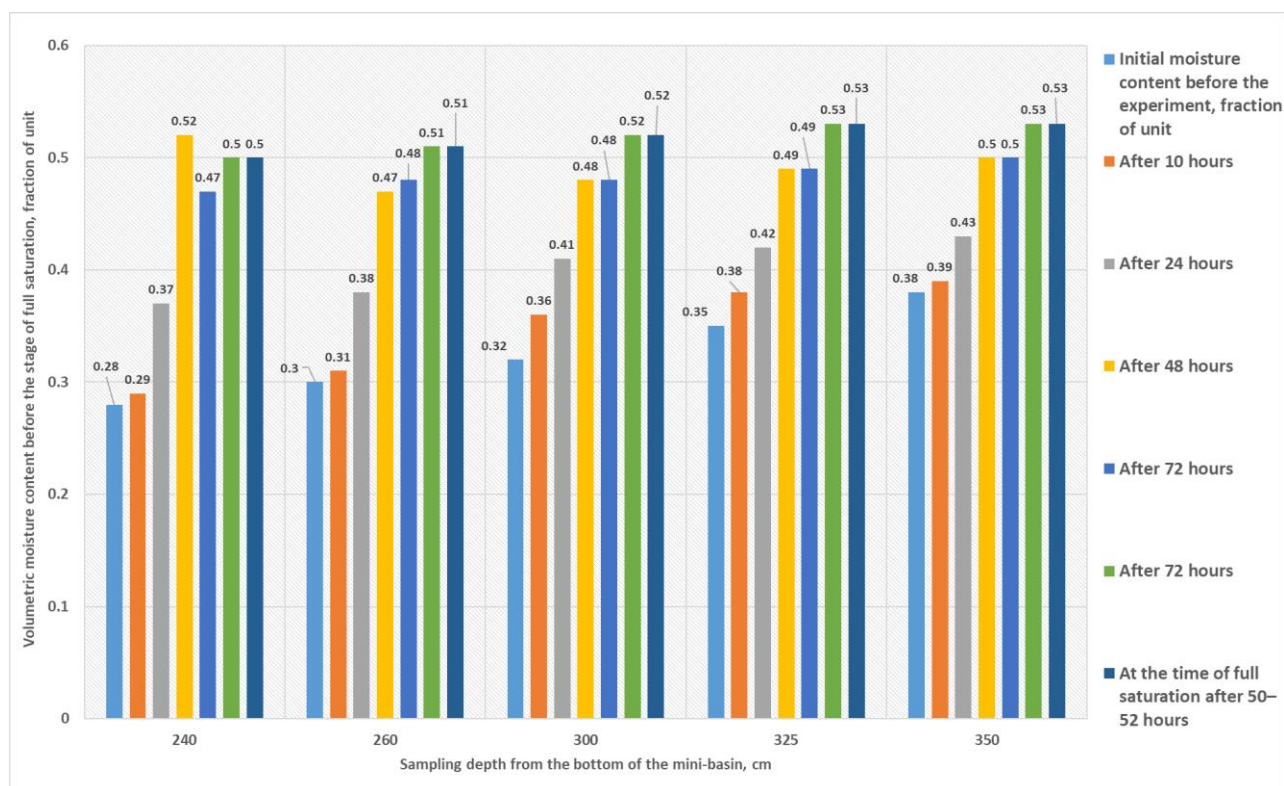


Fig. 8: Field-measured turbidity values of Lepsy River water using portable and gravimetric methods.

Table 2: Natural values of volumetric moisture content along the profile during the experiment in a physical model of an infiltration mini-pool, fractions of a unit.

Sampling depth from the bottom of the mini-basin, cm	Initial moisture content before the experiment, fraction of unit	Volumetric moisture content before the stage of full saturation, fraction of unit					At the time of full saturation after 50–52 hours
		After 10 hours	After 24 hours	After 48 hours	After 72 hours	After 72 hours	
240	0.28	0.29	0.37	0.52	0.47	0.51	0.50
260	0.30	0.31	0.38	0.47	0.48	0.52	0.51
300	0.32	0.36	0.41	0.48	0.48	0.53	0.52
325	0.35	0.38	0.42	0.49	0.49	0.53	0.53
350	0.38	0.39	0.43	0.50	0.50	0.52	0.53

**Fig. 9:** Volumetric moisture content along the profile during the experiment in a physical model of an infiltration mini-pool, fractions of a unit.**Table 3:** Results of optical density measurements as a function of Turbidity.

Turbidity, mg/L	5	12.5	20	27.5	35	42.5	50
Optical density, units	0.1	0.2	0.3	0.4	0.6	0.8	1.0

grained sands with gravel, 1.32 to 1.64 m/day for fine sands, 1.10 to 1.18 m/day for sandy loams, and 0.11 to 0.79 m/day for clay loams. These values were validated using Hazen's empirical formula, showing an average deviation within 3.8–14.7% for sands and 1.1–5.4% for loams (Fig. 8).

Volumetric moisture content was measured in the vadose zone using intact soil cores taken before and after infiltration. The observed moisture profiles were visualized as chronosopleths over a 96-hour period (Table 2 and Fig. 9). Maximum saturation occurred within 50–72 hours, indicating a gradual percolation front through variably permeable layers. The variation of density with turbidity was presented in Table 3 and Fig. 10. The optical density results presented in Table 3 and Fig. 10 reinforce the consistency and accuracy of turbidity

measurements obtained through both field and laboratory methods. These findings provide a reliable basis for assessing suspended sediment concentrations during infiltration events. The data presented above conclude the results section, and the following discussion interprets their broader implications for the design and implementation of MAR systems at the Lepsinsky site and comparable semi-arid regions.

3.2 Discussion

The experimental results confirm the suitability of the Lepsinsky site for small-scale MAR implementation under low-flow hydrological conditions. The layered structure of the vadose zone, comprising alternating permeable sands and semi-permeable loams, provides both sufficient infiltration



Fig. 10: The variation of density with turbidity.

capacity and potential natural filtration for quality enhancement. The calculated KF values align with known benchmarks for respective soil types and display good agreement with Hazen-based estimates, especially in sandy-gravel horizons. The minor discrepancies (<15%) are attributed to natural heterogeneity and test condition variabilities, but are within acceptable engineering margins.

These observations are consistent with recent international research findings. For example,^[13] conducted a systematic review of potential contaminant pathways through MAR systems and emphasized the importance of real-time turbidity and chemical monitoring for protecting aquifer integrity.^[7] Demonstrated that site-specific MAR designs, when informed by hydrological and water quality data, can significantly enhance recharge efficiency and reduce environmental risks. Integrating such insights into local MAR planning in Kazakhstan can improve operational resilience and guide adaptive management frameworks.

Moisture profile tracking revealed efficient water migration through the unsaturated zone, reaching significant depths (up to 0.52 m volumetric water content) by the third day. These results indicate favorable conditions for artificial recharge through surface infiltration under controlled input regimes. Water quality observations reinforce the potential for MAR application, given the low turbidity and biological contamination in the source river.

The study's grain-size analysis indicated effective grain diameter (d_{10}) values ranging from 0.09 mm in clay loam horizons to 0.45 mm in coarse sands with gravel inclusions, based on cumulative particle-size distribution curves (Fig. 4). According to established MAR guidelines,^[19,26] sediment layers with $d_{10} < 0.1$ mm are considered highly susceptible to

surface clogging due to fine particle retention and rapid biological and chemical fouling. Conversely, layers with d_{10} between 0.25 and 0.50 mm are generally optimal for infiltration, offering a balance between hydraulic conductivity and filter stability. At the Lepsinsky site, the dominant infiltration layers (medium and coarse sands) fall within the favorable range of $d_{10} = 0.28\text{--}0.45$ mm, suggesting low colmatation risk under baseline conditions. Clay-dominated horizons with $d_{10} < 0.1$ mm were either excluded from recharge zones or treated as barrier layers limiting vertical migration. This alignment between observed d_{10} values and established colmatation risk thresholds supports the earlier conclusion regarding favorable infiltration conditions. Nevertheless, periodic sediment flushing or pre-screening may be necessary if surface deposits shift due to hydrological variability or sediment transport from the river channel. The successful application of the Turb 350 IR WTW turbidimeter in combination with traditional gravimetric analysis and laboratory spectrophotometry demonstrates the feasibility of rapid, accurate turbidity monitoring in remote field conditions.

While the field calibration of portable turbidity meters against gravimetric analysis yielded a strong correlation ($R = 0.90$), the interpretation of turbidity values in a regulatory and operational context is critical. According to international guidelines and regional water quality standards, turbidity levels below 5 NTU are typically considered acceptable for infiltration in MAR systems, as higher levels increase the risk of clogging due to suspended solids accumulation.

At the Lepsinsky site, the measured turbidity values of the Lepsy River ranged from 3.1 to 6.8 NTU, with higher values observed during periods of elevated discharge in late spring and early summer, corresponding to snowmelt and glacial

runoff events. This seasonal pattern suggests that increased sediment load correlates with high-flow conditions, which could intensify the risk of infiltration media colmatation if untreated.

To improve spatial and lithological clarity, Figs. 2 and 3 have been revised to include scale bars, coordinate grid references (WGS 84), and clearly labeled features such as the infiltration trench, hydrological monitoring station, Lepsy River channel, floodplain terraces, and aeolian dune boundaries. These additions enhance the interpretability of the site's geomorphological and hydrogeological context. Furthermore, Fig. 4 has been updated to specify sampling depths corresponding to each sediment type shown in the grain-size distribution curve. This detail provides critical context for understanding the relationship between particle-size parameters (*e.g.*, d_{10}) and colmatation potential across vertical profiles. Incorporating depth-specific lithological information supports more accurate interpretation of filtration behavior and infiltration design for MAR systems.

Turbidity fluctuations directly impact the efficiency of infiltration and the longevity of MAR infrastructure. Elevated turbidity promotes the formation of clogging layers at the sediment–water interface, reducing hydraulic conductivity and necessitating more frequent maintenance or pretreatment interventions. The Lepsinsky site's low average turbidity during base flow conditions supports the viability of direct infiltration without pre-filtration. However, a dynamic operational strategy should be implemented to limit recharge during high-turbidity periods and prioritize infiltration when turbidity remains within acceptable thresholds.

Future monitoring should incorporate automated turbidity logging and flow correlation analysis to refine seasonal operation schedules and improve infiltration system resilience.

Overall, the findings support the use of the studied infiltration basin configuration and monitoring setup for future MAR installations in southeastern Kazakhstan, especially under decentralized water supply frameworks for rural areas.

A limitation of this study is the absence of a comprehensive chemical characterization of the groundwater. Parameters such as total dissolved solids (TDS), water hardness, and the presence of potential contaminants (*e.g.*, nitrates, heavy metals, or persistent organic pollutants) were not included in the current monitoring protocol. These indicators are essential for assessing the aquifer's suitability for potable water storage and should be incorporated in future research to ensure compliance with public health standards and sustainable MAR system performance.

4. Conclusion

The comprehensive experimental investigations conducted at the Lepsinsky site have provided robust evidence supporting the feasibility of managed aquifer recharge (MAR) under semi-arid conditions in southeastern Kazakhstan. Field data confirmed sufficient infiltration capacity of cover sediments

(ranging from coarse sands to loams), reliable moisture propagation through the vadose zone, and effective reduction of turbidity during infiltration.

This study presents several novel contributions. For the first time in southeastern Kazakhstan, field-scale infiltration experiments were conducted with a combination of in-situ turbidity monitoring, chrono-isopleth moisture profiling, and grain-size-based clogging risk assessment. The integration of portable turbidity sensors with traditional gravimetric validation provides a practical framework for low-cost, high-accuracy monitoring of MAR systems in remote, data-scarce environments. Additionally, the detailed lithological and stratigraphic mapping of the Lepsinsky site revealed the presence of naturally layered sedimentary sequences—medium to coarse sands alternating with semi-permeable loams—uniquely suited for passive filtration during recharge. This geohydrological configuration had not been previously characterized for MAR potential in this region and may serve as a baseline for identifying similar recharge-prone zones across the Balkhash-Alakol basin.

The practical significance of the study lies in its direct applicability to rural and agricultural water management in regions facing water scarcity. The tested MAR configuration offers a replicable solution for decentralized water supply, contributing to groundwater sustainability and climate adaptation strategies in arid environments. However, the study has certain limitations. Notably, the chemical composition of groundwater was not analyzed in detail. Key parameters such as mineralization, hardness, and the presence of specific pollutants (*e.g.*, nitrates, heavy metals, or organic contaminants) were not included, limiting the assessment of water quality compliance for potable use. In addition, the short-term nature of the field campaign did not account for seasonal variability or long-term recharge effects.

Future research should address these gaps by: incorporating hydrochemical and microbiological monitoring of recharge and groundwater quality; assessing seasonal dynamics in infiltration behavior and clogging potential; evaluating the long-term performance and maintenance needs of MAR systems under repeated operational cycles; and exploring the scalability of such systems under varying climatic, geological, and socio-economic conditions. These directions will strengthen the scientific basis for MAR applications and support evidence-based decision-making for sustainable groundwater resource management in Kazakhstan and beyond. In addition, the scalability of MAR systems warrants consideration. While the Lepsinsky site demonstrates suitability for small-scale, decentralized recharge applications, the transferability of this approach to larger or more urbanized contexts poses operational and economic challenges. Seasonal variations in river discharge, particularly peak flows during snowmelt periods, may lead to overloading of infiltration basins and increased colmatation risks, requiring adaptive infrastructure such as sedimentation forebays or dynamic intake regulation.

Moreover, economic feasibility differs significantly between rural and urban areas. In rural regions, the relatively low infrastructure cost and decentralized nature of MAR may make it an attractive option for agricultural irrigation and livestock water supply. In contrast, urban MAR systems often require higher initial investment in water pretreatment, land acquisition, and monitoring technologies to comply with regulatory standards for potable use.

Policymakers and practitioners should therefore tailor MAR system designs to specific hydrogeological, economic, and institutional contexts. Strategic planning must include cost-benefit analyses, stakeholder engagement, and long-term maintenance frameworks to ensure sustainable recharge operations at scale.

Acknowledgements

This research was funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan grant no. AP19174932: Study of colmatation processes under experimental conditions of artificial replenishment of groundwater reserves in South-Eastern Kazakhstan. We greatly appreciate the support of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

CRedit Statement

Aida Ismagulova and **Nurbol Tileuberdi**: Data curation, Data visualization, Formal analysis, Methodology, Writing – original draft. **Vitaly Kulagin**: Resources, Writing – review & editing. **Adiya Zhumabek** and **Aigul Issagaliyeva**: Data curation, Validation, Writing – review & editing. **Nurbol Itemen**: Supervision, Funding acquisition, Writing – review & editing. **Ahmed N. Al-Dujaili**: Conceptualization, Supervision, Writing – review & editing.

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