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ASSESSING GROUNDWATER FOR MANAGED AQUIFER RECHARGE IN EASTERN KAZAKHSTAN

Groundwater in Kazakhstan is becoming an increasingly vital resource for ensuring long-term water and food security in the face of climate change, growing population demands, seasonal variability, and limited surface water availability. This study evaluates groundwater quality and soil infiltration capacity in Eastern Kazakhstan to assess the potential for implementing Managed Aquifer Recharge (MAR) as a sustainable water management approach. Hydrochemical analysis revealed predominantly calcium–magnesium bicarbonate waters with low mineralization, suitable for both irrigation and domestic use, indicating generally good groundwater quality. Field tests conducted using the Boldyrev infiltration method demonstrated moderate to high soil permeability in alluvial and sandy-gravel deposits, confirming favorable recharge conditions. Among the areas studied, the Zharbulak, Katynsuy, and Kuraylin deposits were identified as the most promising sites for MAR pilot projects. Overall, the results highlight MAR as a practical, cost-effective, and climate-resilient tool for strengthening regional water security and supporting sustainable agricultural development in Kazakhstan.

Keywords: groundwater quality, Managed Aquifer Recharge (MAR), Boldyrev infiltration method, hydrochemical analysis, Eastern Kazakhstan Ayagoz river basin, climate adaptation, irrigation water management, sustainable agriculture.

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Шығыс Қазақстандағы жерасты суларын басқарылатын толықтыру мүмкіндіктерін бағалау

Қазақстандағы жерасты сулары климаттың өзгеруі, маусымдық құбылмалылық және жерүсті суларының шектеулі қолжетімділігі жағдайында елдің су және азық-түлік қауіпсіздігін қамтамасыз етуде барған сайын маңызды әрі стратегиялық табиғи ресурсқа айналуда. Соңғы жылдары су тапшылығының артуы мен экожүйелік тепе-теңдіктің бұзылуы бұл ресурсты тиімді пайдаланудың өзектілігін арттырды. Осы зерттеу барысында Шығыс Қазақстан өңіріндегі жерасты суларының сапасы мен топырақтың инфильтрациялық қасиеттері кешенді түрде зерттеліп, басқарылатын су қабатын толықтыру (Managed Aquifer Recharge, MAR) технологиясын енгізудің экологиялық, техникалық және әлеуметтік тұрғыдан тиімділігі жан-жақты бағаланды. Гидрохимиялық талдау нәтижелері минералдануы төмен, негізінен кальций-магнийлі гидрокарбонат типті сулардың басым екенін көрсетті, бұл олардың ауыл шаруашылығында суару, мал шаруашылығы және тұрмыстық қажеттіліктер үшін кеңінен пайдалануға жарамды екенін дәлелдейді. Бодырев әдісімен жүргізілген инфильтрациялық сынақтар аллювийлі және құмды-қиыршық тасты шөгінділердің орташа және жоғары өткізгіштігін растады, бұл жер асты суларын толықтыруға өте қолайлы табиғи жағдайлар бар екенін айқындайды. MAR пилоттық жобалары үшін Жарбулак, Қатынсу және Құрайлы учаскелері ең перспективалы аймақтар ретінде анықталды. Алынған нәтижелер MAR технологиясының климатқа бейімделген, экологиялық, экономикалық және әлеуметтік тұрғыдан тиімді әрі болашағы зор шешім екенін дәлелдейді.

Түйін сөздер: жерасты суларының сапасы, басқарылатын су қабатын толықтыру (MAR), Бодырев инфильтрация әдісі, гидрохимиялық талдау, Шығыс Қазақстан, Аягөз өзені алабы, климаттың өзгеруіне бейімделу, суармалы суды басқару, тұрақты ауыл шаруашылығы.

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Оценка подземных вод для управляемого пополнения водоносных горизонтов в Восточном Казахстане

Подземные воды в Казахстане становятся всё более значимым и стратегически важным природным ресурсом для обеспечения долгосрочной водной и продовольственной безопасности в условиях изменения климата, сезонной изменчивости, роста потребления и ограниченной доступности поверхностных водных источников. В данном исследовании подробно оцениваются качество подземных вод и инфильтрационная способность почв в Восточном Казахстане с целью определения потенциала внедрения технологии управляемого пополнения водоносных горизонтов (Managed Aquifer Recharge, MAR) как устойчивого инструмента водного менеджмента. Гидрохимический анализ показал преимущественно кальций-магниевые гидрокарбонатные воды с низкой минерализацией, что делает их пригодными как для орошения сельскохозяйственных культур, так и для хозяйственно-питьевых нужд населения. Полевые испытания методом инфильтрации по Бодыреву выявили среднюю и высокую проницаемость почв в аллювиальных и песчано-галечниковых отложениях, что подтверждает наличие благоприятных природных условий для пополнения запасов подземных вод. Наиболее перспективными участками для реализации пилотных проектов MAR определены Жарбулакское, Катынсуское и Курайлинское месторождения. Полученные результаты указывают, что технология MAR является практичным, экологически безопасным и устойчивым к климатическим изменениям решением, способным укрепить водную безопасность и способствовать развитию устойчивого сельского хозяйства в Казахстане.

Ключевые слова: качество подземных вод, управляемое пополнение водоносных горизонтов (MAR), метод инфильтрации по Бодыреву, гидрохимический анализ, Восточный Казахстан, бассейн реки Аягоз, адаптация к изменению климата, управление оросительными водами, устойчивое сельское хозяйство.

Introduction

As global water scarcity intensifies, ensuring access to sustainable freshwater sources has become a critical challenge. Groundwater, often referred to as the “hidden resource,” is increasingly recognized as a vital buffer against climate variability and declining surface water supplies, particularly in supporting agriculture and food security (Taylor et al., 2013; United Nations, 2022). The sustainable use of groundwater is also central to the sixth United Nations Sustainable Development Goal (SDG 6).

Globally, reliance on groundwater is rising. Over the past 30 years, more than 300 million wells have been drilled, with annual withdrawals reaching 959 km^3 by 2017–68.5% of which occurred in Asia (Absametov, 2023; United Nations, 2022). Countries such as India, China, and Pakistan use up to 76% of their groundwater resources for agriculture, underscoring the urgent need for integrated and conjunctive management of surface and groundwater resources (Shtengelov, 1988).

In Kazakhstan, groundwater resources are gaining importance due to increasing limitations on surface water (Absametov et al., 2023). The chemical composition of groundwater is influenced by water–rock interactions in mountainous regions and water–soil–gas processes in lowlands (Mukhamedjanov et al., 2018). In certain areas, elevated concentrations of sulfates, sodium, and chloride exceed permissible drinking water standards (Adenova et al., 2024). These conditions highlight the need for systematic hydrochemical assessment and resource evaluation to support groundwater use for irrigation and climate adaptation.

Despite considerable reserves, groundwater remains underutilized in Kazakhstan. Currently, there is no comprehensive framework for integrating Managed Aquifer Recharge (MAR) into national water management strategies. This study addresses that gap by evaluating the hydrochemical status and resource potential of groundwater deposits in Eastern Kazakhstan and exploring the feasibility of MAR as a tool for enhancing climate resilience.

The aim of this study is to assess groundwater quality in the context of Managed Aquifer Recharge (MAR) and to evaluate soil infiltration capacity using the Boldyrev method. The research provides recommendations for maintaining high water quality to ensure the successful implementation of MAR, while emphasizing its importance for sustainable use in agriculture, domestic water supply, and other sectors. Specifically, the study examines how water quality affects the effectiveness of MAR systems, emphasizing the need for systematic treatment and monitoring to prevent groundwater contamination. In addition, the Boldyrev infiltration method is applied to determine soil permeability and identify sites with favorable conditions for recharge, thereby contributing to a more comprehensive understanding of MAR implementation in the Ayagoz River basin.

International Solutions in Managed Aquifer Recharge (MAR)

Countries such as Australia, Brazil, France, Germany, Israel, Spain, and the United States have demonstrated significant success in integrating Managed Aquifer Recharge (MAR) into their water management systems. MAR is widely recognized as a crucial approach to sustainable water resource management, involving the controlled infiltration of water into aquifers to replenish groundwater storage and, in many cases, to enhance water quality (Dillon, 2005; Maliva, 2020). This method has gained global attention as a key strategy to mitigate water scarcity, improve groundwater sustainability, and strengthen resilience to droughts (Bouwer, 2002). However, its implementation requires careful assessment of groundwater quality to ensure both safety and long-term effectiveness (Page et al., 2010).

Israel and Spain provide striking examples of successful MAR applications. Israel recycles nearly 90% of its wastewater, primarily for agricultural use, significantly reducing dependence on freshwater resources and lowering water supply costs (Adar et al., 2012). In Spain, infiltration basins and aquifer recharge systems have directly contributed to the stability of irrigated agriculture, helping to mitigate the impacts of drought and optimize water use efficiency (Sprenger et al., 2017).

In the United States, MAR projects are actively supported through government initiatives. California's Flood-MAR program exemplifies this approach by capturing excess surface water during flood events and directing it into aquifers. These projects not only reduce flood risks but also ensure a reliable water supply for agriculture and lower infrastructure costs by decreasing reliance on large surface reservoirs (California Department of Water Resources, 2018).

Australia is also considered a global leader in MAR, particularly in arid regions such as Adelaide and Perth, where aquifer recharge programs enhance drinking water security and stabilize urban water supplies (Dillon et al., 2009).

In Brazil, MAR is implemented in drought-prone northeastern states, where the infiltration of rainwater and treated wastewater reduces dependence on surface water and increases resilience to agricultural water shortages (da Silva et al., 2015).

Across Europe, France and Germany primarily employ MAR for water quality protection and urban water supply security. In France, MAR projects in the Paris region help maintain a consistent supply of high-quality drinking water (Greskowiak et al., 2018). In Germany, recharge projects in river valleys such as the Elbe and Rhine are essential for stabilizing groundwater resources and ensuring reliable urban water supply (Schwinn et al., 2017).

Adaptation for Kazakhstan

While international practices demonstrate that Managed Aquifer Recharge (MAR) can strengthen agricultural resilience, water security, and cost efficiency, Kazakhstan remains at an early stage of adopting these technologies. Despite possessing vast groundwater reserves, groundwater uses accounts for only 3.7–5% of the nation's total annual water intake (Smolyar et al., 2012a). In agriculture, utilization is critically low–only 0.15–0.21 km³ per year is extracted for irrigation, compared to an estimated potential of 7.76 km³ annually (Mukhamedzhanov & Dzhabasov, 1988; Absametov, 2024).

This underutilization is attributed to outdated regulations, fragmented institutional frameworks, and insufficient monitoring systems that hinder effective groundwater governance (Bekkulova et al., 2021). When compared to global best practices, Kazakhstan's groundwater utilization remains significantly below that of European and Asian countries (Smolyar et al., 2012b).

Unlocking this untapped potential will be essential for strengthening the resilience of Kazakhstan's agricultural sector amid growing climate pressures and increasing dependence on vulnerable surface water supplies. Immediate priorities include:

- refining groundwater resource assessments;
- developing rational models for conjunctive use of surface and groundwater;
- implementing robust monitoring and management systems.

By adopting MAR and aligning national policies with global best practices, Kazakhstan could substantially enhance its water and food security, support sustainable agricultural development, and mitigate climate-related risks (Sydykov & Shlygina, 1998; Absametov, 2020; National Atlas of Kazakhstan, 2010).

Study Area: Eastern Kazakhstan (Abai Region)

The study area is situated in Eastern Kazakhstan, encompassing the Abai Region and part of the East Kazakhstan Region(figure 1). This territory is regarded as one of the most water-abundant areas in the Republic of Kazakhstan, as it contains both surface and groundwater resources. Favorable hydrogeological conditions for aquifer recharge are created by relatively prominent levels of atmospheric precipitation and the widespread presence of fractured and unconsolidated rock formations (Taylor et al., 2013; Absametov, 2023).

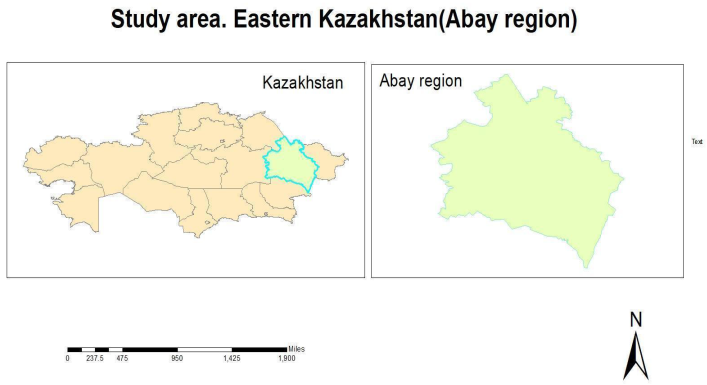

Figure 1 – Study area map of Eastern Kazakhstan (Abai Region)
Source: compiled by the author

Hydrologically, the region belongs to the Irtysh River basin and the endorheic lake systems of the Balkhash–Alakol depression. Under average hydrological conditions, total surface water resources are estimated at approximately 35.92 km³ per year, decreasing to 20.62 km³ in dry years (Figure 2). Of this volume, only 3.54 km³ per year are considered available for practical use, falling to 1.92 km³ in drought years. The Irtysh River and its tributaries are regulated by nearly 20 reservoirs, which are utilized for water supply, hydropower generation, and irrigation (Smolyar & Burov, 2002; Medeu, 2010).

Groundwater resources are also substantial. Forecasted reserves with salinity levels up to 3 g/L are estimated at 6.28 km³ per year, including 5.58 km³ of water with salinity below 1 g/L. Natural recharge is about 5.74 km³ annually, while exploitable reserves are around 2.39 km³ per year, of which 2.20 km³ are suitable for drinking and domestic use (Smolyar et al., 2012a; Committee for Water Resources, 2020). Despite this potential, irrigation in the region still depends almost entirely on surface water (FAO, 2016). The total irrigated area is 197,604 hectares, but only 93,804 hectares (47.5%) are actively cultivated.

Groundwater circulation reflects the geological structure of the area. In the mountain-folded zones, unconfined fissured waters dominate at shallow depths and are associated with zones of intensive rock fracturing, while fissure-vein waters occur along tectonic fault zones. In artesian basins, typically found in closed intermountain depressions, groundwater is contained within porous and intergranular layers. Recharge is primarily driven by the infiltration of precipitation and the percolation of surface runoff, particularly in alluvial fans, foothill plains, and river valleys (Mukhamedzhanov & Dzhabasov, 1988; Absametov, 2020).

The main aquifers and hydrogeological complexes of practical importance include (Figure 3):

- Quaternary alluvial sandy and gravel–pebble deposits in the valleys of the Irtysh, Ayagoz, and their tributaries;
- Small alluvial cones and tectonic depressions;
- Cretaceous and Paleogene sandy deposits of the Nizhnevartovsk–Petropavlovsk Basin;
- Lower to Middle Paleozoic effusive–sedimentary and intrusive rocks that serve as fractured and fissured aquifers (Smolyar et al., 2002; Medeu, 2010).

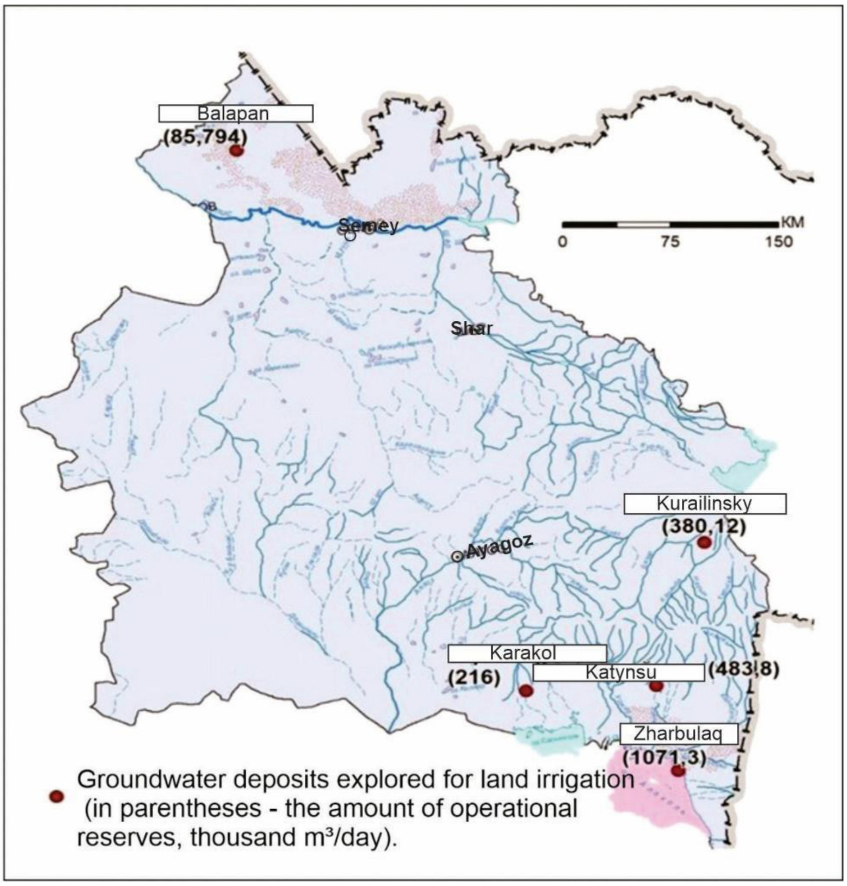

Figure 2 – Map of operational groundwater deposits in the Abai Region
Source: compiled by the author on data from the Committee for Water Resources (2020), Kazhydromet (2021), and the National Atlas of the Republic of Kazakhstan (2010)

According to national hydrogeological assessments, groundwater resources with salinity up to 3 g/L are estimated at 2.71 km³ per year, including 2.05 km³ with salinity below 1 g/L. Natural recharge is estimated at 2.74 km³ per year, while exploitable reserves reach 1.30 km³ annually, of which 1.17 km³ are suitable for drinking purposes (National Atlas of the Republic of Kazakhstan, 2010; Absametov, 2024).(Figure 3)

All lithological units contain groundwater of acceptable quality, with the highest yields associated with loose detrital formations (Smolyar et al., 2012b).

A special focus of this study is the Ayagoz River basin, which is both hydrologically and ecologically significant. The Ayagoz River originates on the northern slopes of the Tarbagatai Mountains and flows approximately 492 km, draining a catchment area of 15,700 km² before discharging into Lake Balkhash. The basin encompasses diverse landscapes, ranging from mountainous terrain in the upper reaches to semi-desert and steppe zones downstream. It is characterized by chestnut soils, an average discharge of 8.8 m³/s, and suspended sediment loads reaching up to 0.8 kg/s (ile-balkhash.kz, n.d.; Kazhydromet, 2021).

Compared to other intermittent rivers in the region, the Ayagoz River exhibits greater seasonal variability and hydrological activity, making it a representative case for analyzing surface–groundwater interactions, sediment transport, and water management challenges in the semi-arid and arid zones of Kazakhstan (FAO, 2016).

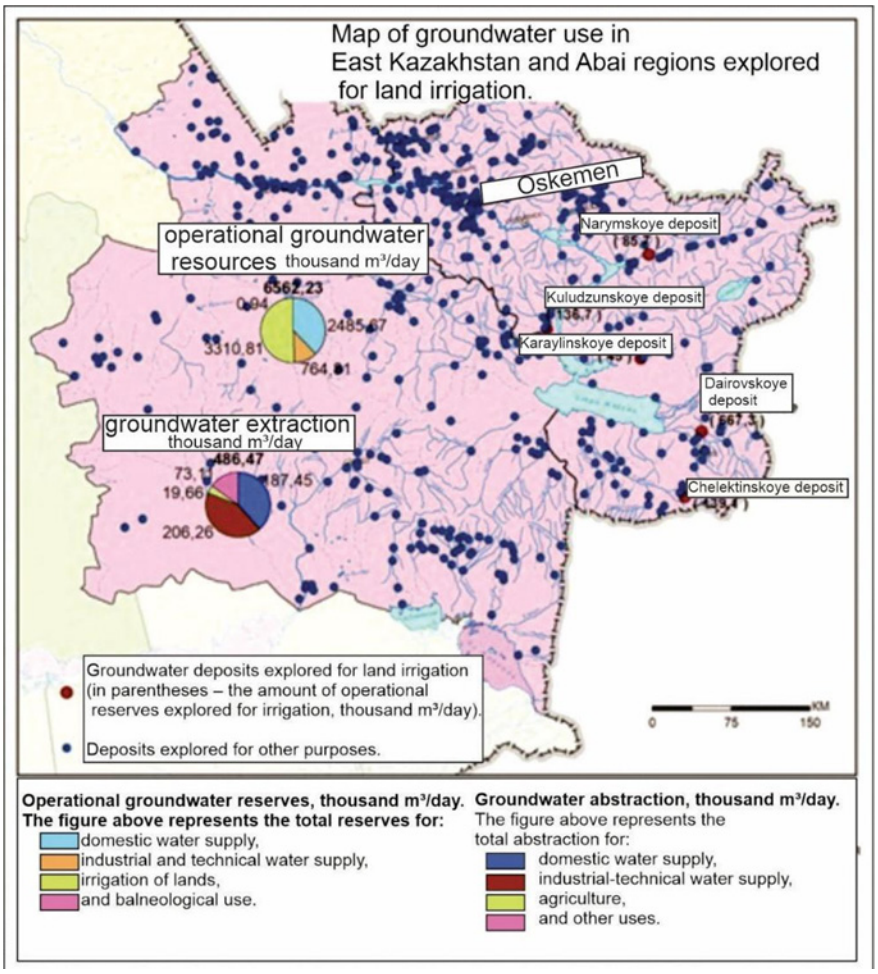

Figure 3 – Map of groundwater use in East Kazakhstan and Abai, explored for irrigation
Source: compiled by the author based on data from the Committee for Water Resources (2020), Kazhydromet (2021), and GIS analysis

This combination of climatic, geological, and hydrological diversity provides favorable conditions for long-term monitoring and analysis of water resources in Eastern Kazakhstan and underscores the region's importance for developing groundwater-based climate adaptation strategies.

Materials and methods

The methodological framework of this study was designed to assess the hydrochemical characteristics, infiltration capacity, and groundwater resource potential in Eastern Kazakhstan and the Abai Region, with a focus on evaluating their suitability for Managed Aquifer Recharge (MAR) implementation. The workflow integrates hydrochemical, hydrological, and field-based infiltration analyses to identify optimal locations for MAR pilot projects. The overall framework of the study is illustrated in Figure 4.

The primary objective of the study was to determine groundwater quality and soil permeability to support the selection of potential MAR sites suitable for irrigated agriculture and sustainable water resource management. Both laboratory and field-based approaches were employed to quantify recharge potential and assess the technical feasibility of artificial aquifer replenishment as a climate adaptation tool. Groundwater samples were collected from wells and springs distributed across the study area. Laboratory analyses were performed to determine the concentrations of major ions–calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), bicarbonate (HCO_3^{-}), sulfate (SO_4^{2-}), and chloride (Cl^{-}). The results were processed using AquaChem software and interpreted through Piper and Durov diagrams to identify hydrochemical facies and classify groundwater types. The analysis provided insight into groundwater mineralization, pH balance, and overall chemical stability, which are crucial for evaluating the safety and suitability of groundwater for both recharge and irrigation purposes. To determine the sustainability of local aquifers, the study calculated the natural (V_n) and elastic (V_e) reserves, sustainable yield (Q_s), and the provision coefficient ($K_o b_e s$)–the ratio between available groundwater reserves and current abstraction levels. Sites where $K_o b_e s > 1$ were considered hydrologically sustainable and potentially suitable for controlled recharge operations. This stage provided a quantitative foundation for evaluating the long-term capacity of aquifers to receive additional recharge without causing overexploitation or degradation of groundwater quality.

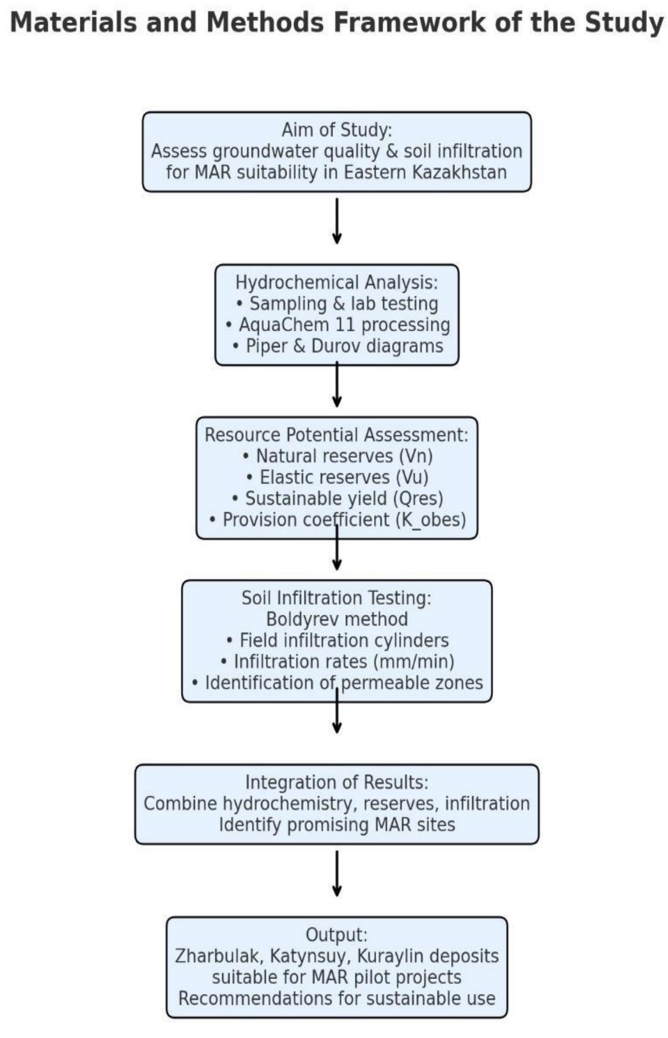

Figure 4 – Research methodology
Source: compiled by the author based on literature review and field data analysis

Field infiltration experiments were conducted using the Boldyrev method, which employs double-ring infiltration cylinders installed at representative points across the study sites. Measurements of infiltration rates (mm/min) were recorded to assess the permeability of surface and subsurface layers. The highest infiltration capacities were observed in alluvial cones, sand-gravel deposits, and river terrace zones, indicating that these geological formations are particularly favorable for recharge through infiltration-based MAR systems.

All hydrochemical, hydrological, and infiltration datasets were integrated using GIS-based spatial analysis to delineate areas with the highest recharge potential. The integrated results identified three priority zones–Zharbulak, Katynsu, and Kuraylin–as optimal locations for MAR pilot implementation. These sites exhibit chemically stable groundwater, adequate aquifer reserves, and favorable soil infiltration characteristics. The adopted multi-stage methodology demonstrated the effectiveness of combining field-based infiltration experiments, hydrochemical assessment, and quantitative groundwater evaluation for identifying MAR potential under arid and semi-arid conditions. This approach provides a robust scientific foundation for the expansion of MAR practices in Kazakhstan, contributing to sustainable groundwater management, enhanced irrigation efficiency, and improved resilience to water scarcity and climate variability.

Hydrochemical Analysis and Data Processing

Hydrochemical data were processed using AquaChem 11 (Waterloo Hydrogeologic, Canada), a software package widely used in hydrogeological and hydrochemical studies. Laboratory results of groundwater samples were entered into the software database for verification, consistency checks, and interpretation.

The analytical workflow included the following steps:

- Quality control – recalculation of ion balance and validation of laboratory analyses.

- Determination of total dissolved solids (TDS) to assess the degree of mineralization.

- Classification of groundwater types based on major ion composition.

- Visualization of hydrochemical facies, including:

- Piper diagram for identifying the relative proportions of major cations (Ca^{2+}, Mg^{2+}, Na^{+}+K^{+}) and anions (Cl^{-}, SO_4^{2-}, HCO_3^{-}+CO_3^{2-}) *(*Figure 5*)*.

- Durov diagram for comprehensive evaluation of macro-component composition, mineralization levels, and pH.

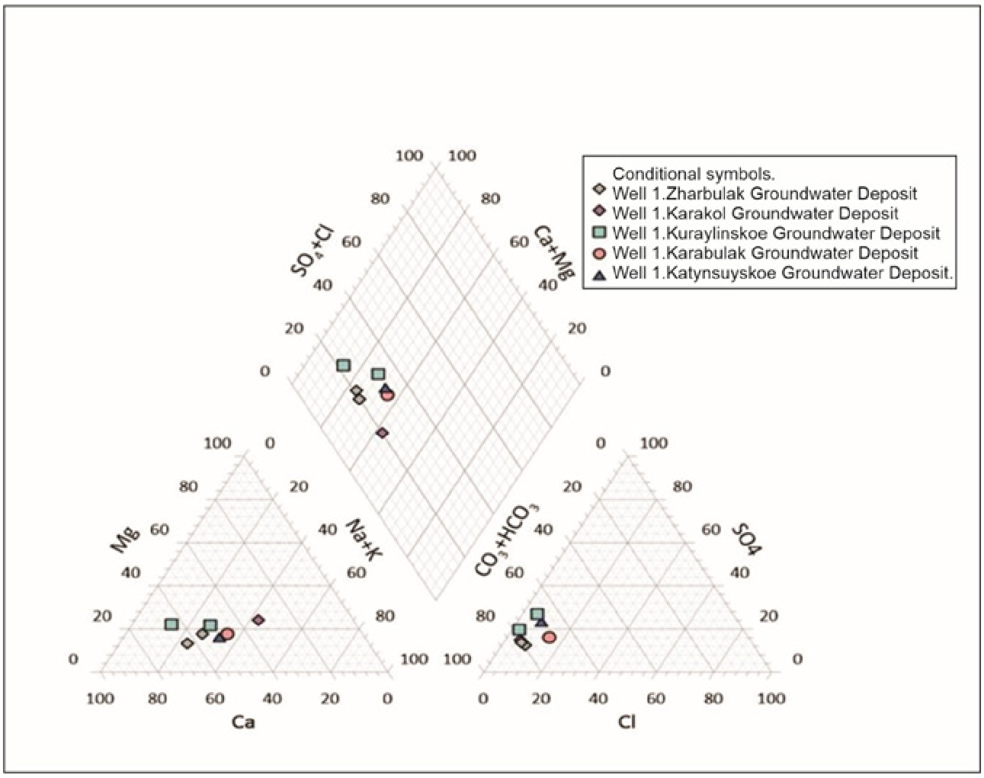

Figure 5 – Piper diagram of groundwater chemistry in the Abai Region
Source: compiled by the author based on hydrochemical
data from Kazhydromet (2021) and field sampling results (2023)

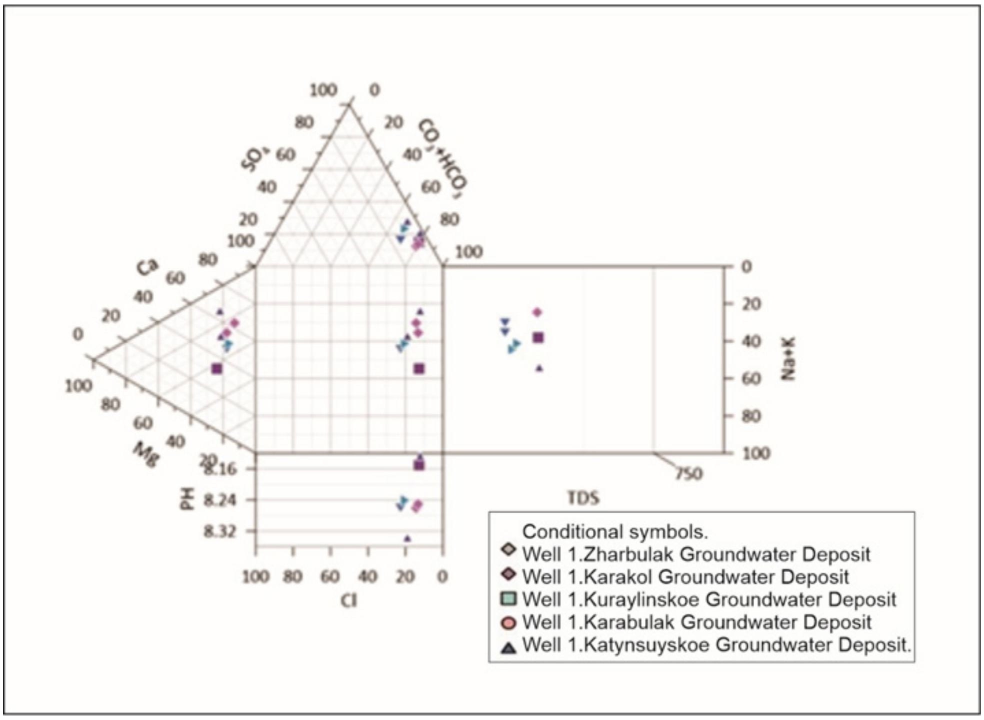

Figure 6 – Hydrochemical classification diagrams of groundwater deposits in the Abai Region
Source: compiled by the author based on hydrochemical monitoring data from Kazhydromet (2021) and the National Atlas of the Republic of Kazakhstan (2010)

Resource Potential Assessment and Provision Indicator Calculation

To evaluate the operational reserves of groundwater and identify sites suitable for MAR implementation, the following formulas were applied:

Calculation of natural (storage) reserves by the formula:

$$V_n = FH\mu \qquad (1.1)$$

where:

V_e – natural (storage) reserves, m³;

F – area within the influence contour, m²;

H – average aquifer thickness, m;

μ – specific yield of the rocks.

Calculation of elastic natural reserves for confined waters by the formula:

$$V_u = \mu F H_{av} \qquad (1.2)$$

where:

V_u – elastic reserves, m³;

μ – elastic yield;

F – aquifer area, m²;

H_{avg} – average head above the aquifer roof, m.

Calculation of water intake based on natural reserves without recharge by the formula:

$$Q_{res} = \frac{a * V_{res}}{t} \qquad (1.3)$$

where:

Q_{res} – water intake from natural reserves, m³/day;

V_{res} – volume of natural reserves, m³;

a – extraction coefficient (0.3 to 0.5);

t – exploitation period, days.

The calculation results were compiled into a summary table (Table A1), providing detailed characteristics of each GWD by mineralization, reserve volume, and provision.

The aggregated data from multiple groundwater deposits in the Abay region reveals significant groundwater reserves. The key findings are as follows:

Total Operational Resource Volume (Qobes): 25.89 m³/s

Total Natural Resource Availability: 2237.0 thousand m³/day

Total Coefficient of Availability (Kobes): 1.79

This indicates that the Abay region has substantial groundwater resources available for use, with efficient extraction practices currently in place. The relatively high Kobes's coefficient suggests that the natural resources exceed the operational requirements, offering a cushion for sustainable water management in the region.

General Observations

Mineralization Levels: The mineralization levels across all deposits in both East Kazakhstan and Abay regions are within acceptable limits (ranging from 0.1 to 1.2 g/L). This indicates that the groundwater is of good quality, requiring minimal treatment before use.

The findings highlight the importance of sustainable groundwater management strategies to maintain this balance, avoid over-extraction, and secure long-term availability for irrigation and drinking purposes.

Soil Infiltration Assessment (Boldyrev Method)

To complement hydrochemical and reserve assessments, the Boldyrev method was applied to evaluate soil infiltration capacity and determine the suitability of recharge sites for MAR (Figure 7).

Figure 7 – Boldyrev method on Abay region
Source: compiled by the author

Field measurements were conducted using infiltration cylinders.

Procedure: water was poured into soil plots, and the absorption rate was measured over time.

Calculation: infiltration coefficient (mm/min or cm/h) was determined for each site.

Interpretation: soils with higher permeability (alluvial fans, sandy-gravel deposits) were identified as optimal for MAR projects.

Decryption of the method

This method provided an additional hydrological dimension to the study, allowing the selection of recharge zones with favorable soil conditions.

Results and Discussion

The analysis of groundwater availability coefficients (Kobes) in the Abai Region showed values ranging from 1.09 to 4.03, indicating that groundwater reserves in several deposits exceed current extraction volumes. Such values suggest a stable water balance and significant potential for implementing Managed Aquifer Recharge (MAR) technologies aimed at restoring and maintaining groundwater reserves. The most promising sites for pilot MAR projects include the Zharbulak (Kobes = 1.86), Katynsu (Kobes = 1.50), and Kurailin (Kobes = 1.79) deposits. Their geological structures, composed of Quaternary and alluvial sediments with high permeability, provide favorable conditions for natural infiltration and groundwater storage. Furthermore, these sites are characterized by low groundwater mineralization (0.2–0.8 g/L), which indicates good water quality and the possibility of safe recharge without risking deterioration of the hydrochemical composition of aquifers. This factor is particularly important since both the quality of recharge and the receiving water determine the overall efficiency and long-term sustainability of MAR systems. The use of clean, low-mineralized water prevents clogging of infiltration structures, mineral precipitation, and soil salinization, while also preserving the natural balance between surface and groundwater systems.

Hydrochemical analysis of samples collected from five monitoring points confirmed that groundwater in the region has high quality and stable chemical properties. The waters are predominantly of the calcium–magnesium–bicarbonate type, typical of naturally low-mineralized groundwater that has not been significantly affected by anthropogenic influences. Mineralization does not exceed 750 mg/L, and the pH values range between 8.16 and 8.32, corresponding to a slightly alkaline environment. This chemical composition indicates a natural origin of groundwater, balanced interaction with host rocks, and the absence of industrial or agricultural contamination. The waters demonstrate high buffering capacity, chemical stability, and suitability for drinking, irrigation, and general agricultural use. For MAR applications, this is a crucial factor, as water quality directly affects infiltration efficiency, aquifer condition, and the preservation of filtration capacity. If water with high concentrations of suspended solids, iron, organic compounds, or salinity is used for recharge, it can lead to clogging of infiltration zones, decreased permeability, and potential aquifer contamination. Therefore, strict control over the quality of both surface and groundwater used for MAR is essential. The parameters of groundwater in the Abai Region meet international standards, making the area particularly favorable for implementing such technologies.

Field infiltration tests conducted using the Boldyrev method helped evaluate the soils' ability to absorb and transmit water. The results showed that the soils of the study sites possess moderate to high permeability, with infiltration coefficients ranging from 3.5 to 6.8 mm/min. The most favorable results were recorded in alluvial fan and sand–gravel deposits, where the structure of the sediments promotes downward water movement and accumulation in aquifers. The high filtration capacity of the sediments, combined with low water mineralization, creates optimal conditions for natural groundwater recharge. Furthermore, the geomorphological characteristics of the terrain – gently sloping valleys and flat areas – promote the accumulation of meltwater and floodwater, which can be directed into specially designed infiltration basins or recharge ponds. Thus, the natural conditions of the Abai Region provide a foundation for developing environmentally safe and economically viable MAR systems.

The combination of hydrochemical, hydrogeological, and infiltration data demonstrates that the selected sites possess the necessary characteristics for pilot MAR implementation. The Zharbulak, Katynsu, and Kurailin deposits can serve as key research and demonstration sites for refining artificial groundwater recharge methods. On a broader scale, MAR implementation in the Abai Region will contribute to enhancing the resilience of regional water resources. This technology allows the storage of excess melt and floodwater during spring for later use in maintaining groundwater levels during dry seasons. Such an approach is particularly relevant for agricultural areas, where water availability directly affects crop yields and economic stability.

In addition, MAR has an important environmental function – it can reduce flooding risks, restore depleted aquifers, and prevent land degradation caused by salinization or erosion. According to international research (Dillon et al., 2019; Maliva, 2014), similar systems have been successfully implemented in India, Australia, California, and Southern Europe, where they contribute not only to groundwater recovery but also to the improvement of entire watershed water balances.

Given increasing climate variability and growing water scarcity in Kazakhstan, MAR technologies are recognized as one of the most promising tools for climate adaptation. In arid and semi-arid regions where surface water is limited and highly seasonal, managed recharge systems can stabilize water balances, ensure continuous water supply, and prevent aquifer depletion. The key condition for successful MAR operation remains the quality of recharge water. Only by meeting hydrochemical and sanitary standards can the natural structure of aquifers be preserved and their contamination or degradation prevented. This requires the development of monitoring systems, regular sampling, and analysis of both chemical (mineralization, ion composition, pH) and physical (turbidity, temperature, color) parameters.

In the context of the Abai Region, the presence of high-quality surface and groundwater creates unique conditions for demonstrating best practices of MAR in Central Asia. The use of these natural advantages will not only improve the regional water balance but also strengthen Kazakhstan's participation in international initiatives for sustainable water management and climate adaptation.

In conclusion, the conducted study confirms that the hydrogeological and hydrochemical conditions of the Abai Region are highly favorable for the implementation of MAR technologies. The combination of low mineralization, stable pH, high permeability of sediments, positive groundwater availability coefficients, and excellent water quality creates the foundation for successful pilot projects. The introduction of MAR systems will not only promote sustainable water use but also enhance climate and food security in the region. Maintaining high water quality during recharge and storage is essential for the long-term effectiveness of MAR and represents a key component of environmentally responsible water management in Kazakhstan climate and environmental stability in eastern Kazakhstan.

Conclusions

This study set out to evaluate the quality of groundwater and the infiltration properties of soils in Eastern Kazakhstan with the goal of identifying opportunities for Managed Aquifer Recharge (MAR). The results show that groundwater in the Abai Region is of decent quality, with low mineralization and stable chemical composition, making it suitable for both irrigation and domestic use. At the same time, the application of the Boldyrev infiltration method confirmed that soils in alluvial and sandy-gravel formations possess sufficient permeability to support recharge operations.

By combining hydrochemical assessments with infiltration testing, the study identified the Zharbulak, Katynsuy, and Kuraylin deposits as promising sites for MAR implementation. These areas demonstrate favorable conditions in terms of water quality, aquifer reserves, and infiltration capacity, providing a reliable basis for future pilot projects.

The findings underline the importance of systematic monitoring and water quality management to safeguard groundwater from contamination and ensure long-term sustainability. More broadly, the integration of MAR into Kazakhstan's water management framework can strengthen agricultural productivity, secure drinking water supplies, and enhance resilience to droughts and climate variability. The Ayagoz River basin, in particular, offers a persuasive case for advancing MAR as part of a climate-adaptive strategy for sustainable groundwater use.

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