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Optimizing Kazakhstan's water budget through subsurface floodwater recharge

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Abstract. The study is dedicated to analyzing the economic efficiency of Managed Aquifer Recharge (MAR) systems as a method of sustainable water supply under the conditions of climate change and water resource scarcity. The work explores the fundamental principles of MAR, its advantages in reducing water supply costs, minimizing water losses, improving resilience to extreme climatic conditions, and maintaining ecosystem balances. Special attention is given to the economic and social benefits that the use of MAR can provide to agriculture and local communities. The research methodology includes an analysis of existing practices, economic modeling, and an assessment of the impact of implementing MAR technologies at the regional level. The results demonstrate that MAR is an effective and economically advantageous strategy for water supply, promoting sustainable use of water resources and improving quality of life. The scientific novelty lies in justifying the economic feasibility of applying MAR systems in the context of climate change, while the practical significance of the study lies in the potential to implement the findings into real-world water resource management practices.

Keywords: *Managed Aquifer Recharge, economic efficiency, water supply, climate change, water resources, sustainable development.*

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1. Introduction

Central Asia (CA) is one of the most vulnerable regions in the world to the consequences of climate change and water scarcity. The region faces changes in precipitation patterns, increased frequency of extreme temperatures, and growing aridity, which negatively affect agriculture, ecosystems, and food security [1]. In Kazakhstan, the problem is exacerbated by a pronounced seasonal water imbalance: during spring, there is an excess of water due to snowmelt and floods, while in the summer months, the country suffers from a shortage of water resources [2]. Traditionally, the focus has been on surface water resources, while the potential of groundwater has been insufficiently utilized [3].

Historically, Kazakhstan and other countries in the region have actively used dams and reservoirs to regulate river flow, irrigate land, and manage flooding. However, the modern practice of dam construction and operation is showing increasing limitations and risks. Key issues include sediment deposition, which leads to a reduction in reservoir capacity by up to 1% annually [4], as well as significant environmental impacts on biodiversity [5]. Furthermore, the construction of large dams involves socio-economic costs, including population displacement and the loss of agricultural land [6]. Climate change exacerbates these problems, causing reservoirs to become less resilient to droughts and extreme precipitation events [7].

In this context, there is a need to explore more sustainable and adaptive approaches to water resource management. One such promising technology is Managed Aquifer Recharge (MAR), which involves collecting and storing surplus surface water underground for future use. Global experience, particularly research from Australia, demonstrates the high efficiency of MAR in agricultural regions with similar conditions. For example, MAR systems in the Little Para and Lockyer valleys contribute up to 8.9 million cubic meters of water annually, with an efficiency rate of up to 67% [8]. In addition to increasing available water reserves, MAR contributes to improved crop yields.

For Kazakhstan, MAR offers an opportunity to simultaneously reduce flood risks, accumulate strategic water reserves, and improve water quality through natural filtration in aquifers. Research conducted in the Zhambyl region has confirmed the presence of areas with high potential for MAR implementation, based on an analysis of soil-hydrogeological conditions [2].

In the context of intensifying climate change and growing demand for water resources, the MAR technology can ensure more sustainable water supply for agriculture, reduce evaporation losses, and minimize ecological risks. The implementation of MAR in Kazakhstan opens up prospects for the sustainable development of the agricultural sector and increased food security in the country.

The goal of this study is to assess the economic feasibility and benefits of using Managed Aquifer Recharge (MAR) technologies as a solution for sustainable water resource management in Kazakhstan. The research focuses on integrating international MAR experience and spatial modeling methods to identify regions where surplus surface water during flood periods can be stored underground for future agricultural use. The overall aim is to provide scientific support for integrating MAR into Kazakhstan's national water resource strategies and raise awareness of MAR as a promising tool for ensuring long-term agricultural and environmental sustainability.The scientific novelty of this research lies in the pioneering application of the economic efficiency assessment method for water storage through Managed Aquifer Recharge (MAR) technologies in Kazakhstan, where water scarcity, particularly in the southern and central regions, is an urgent issue.

2. Materials and methods

The methodological framework of this study focuses on a comparative analysis of international experience in implementing Managed Aquifer Recharge (MAR) technologies, with an emphasis on their economic efficiency and applicability to the conditions of Kazakhstan. The study explores the experiences of Australia, Europe, and the USA, where MAR systems have been successfully integrated into agricultural water supply. Special attention is given to economic indicators cost-benefit ratios, the efficiency of using existing infrastructure, and the impact on crop yield growth.

The implementation of Managed Aquifer Recharge (MAR) technologies in Australia, Europe, and the USA has demonstrated significant economic benefits, particularly in agriculture and urban water management.

In Australia, the active development of MAR began after the 1994 drought, which triggered a major reform in the water sector. The creation of the National Water Plan and the Water Resources Commission contributed to improving the efficiency of water management, reducing water supply costs, and increasing resilience to droughts. Research shows that MAR projects in the Lockyer Valley and the Little Para area achieved up to 67% system efficiency, with annual replenishment volumes ranging from 0.6 to 8.9 million m^3 [8]. These systems not only enhance water security but also contribute to increased agricultural productivity, especially in viticulture [9].

In Europe, countries such as Spain, and in comparative terms, Israel, have focused on MAR. For example, in Israel, around 90% of wastewater is recycled and mainly used for agricultural needs, significantly reducing dependence on freshwater and lowering water supply costs [10]. In Spain, the experience of using infiltration basins and aquifer recharge demonstrated that MAR directly contributes to the economic stability of irrigated agriculture, mitigating the effects of droughts and optimizing water use [11].

In the United States, MAR systems are actively supported by the government through subsidies and special programs. This is particularly evident in California, where Flood-MAR projects aim to capture excess surface water during floods and store it in underground aquifers. These projects not only reduce flood risks but also provide long-term economic benefits through stable water supply for agriculture and reduced costs associated with building expensive surface reservoirs [12].

Managed Aquifer Recharge (MAR) is increasingly seen as an effective tool for sustainable water resource management, particularly under the growing pressure on groundwater. Research in this area focuses on both the economic efficiency and institutional feasibility of MAR projects. The analysis of scientific literature highlights three key approaches to evaluating such projects: through the lens of institutional regulation, economic feasibility at global and local levels, and the assessment of social and environmental benefits.

Reznik emphasize the importance of the institutional environment for the successful implementation of MAR in California, USA. Based on hydroeconomic modeling, the authors demonstrate that the effectiveness of MAR projects directly depends on water rights, coordination between agencies, and management flexibility [13]. The introduction of laws such as the Sustainable Groundwater Management Act (SGMA) creates new incentives for investment in MAR, but in the absence of institutional cooperation, even technically and economically viable projects may be inefficient. This study highlights the role of institutional structures as a key factor in the sustainability of MAR systems.

Ross provides a comparative analysis of 21 MAR schemes in 15 countries, evaluating the levelized cost and the benefit-cost ratio (BCR) [14]. The author shows that systems using natural replenishment through infiltration basins or filtration from rivers exhibit the highest profitability. MAR systems using recycled water are costlier but also yield positive effects. Special attention is given to the unquantified ecological and social benefits, such as groundwater level preservation, water quality improvement, and energy savings. This approach expands the understanding of the cost benefits of MAR beyond direct economic gains.

Halytsia, in a study conducted in Poland, present a rare example of a local economic evaluation of a MAR project considering social and ecological aspects [15]. The authors apply a combined approach: classic cost-benefit analysis (CBA), contingent valuation for calculating the willingness of the population to pay for water quality preservation, and sensitivity analysis to account for uncertainties. The results show that even considering social discounting and potential risks, expanding MAR systems remains beneficial. This study is valuable as an example of a comprehensive approach, including indirect and non-material benefits, and provides a foundation for future policies in sustainable water supply.

In summary, the research underscores that successful MAR implementation depends not only on hydrological and technical conditions but also on institutional support, economic viability, and community engagement. The studies demonstrate a wide range of evaluation methods – ranging from modeling and global meta-analyses to localized practical cases.

Thus, the international experience confirms that MAR systems are an economically efficient solution, contribute to increased agricultural productivity, and support sustainable water resource management. This makes MAR particularly relevant for arid and semi-arid regions like Kazakhstan.

3. Study area

The Chilik River (also known as Shelek) is located in southeastern Kazakhstan, within Almaty Region. It originates on the southern slopes of the Zailiysky Alatau range, in the zone of glaciers and eternal snow, and belongs to the Lake Balkhash basin. The river's length is approximately 245 km, and its catchment area covers about 5090 km^2 [16]. The basin's relief varies from high-mountainous upstream reaches to lowland and foothill terrain in the middle and lower courses, determining both the river's flow regime and the natural conditions affecting land use and water management [17].

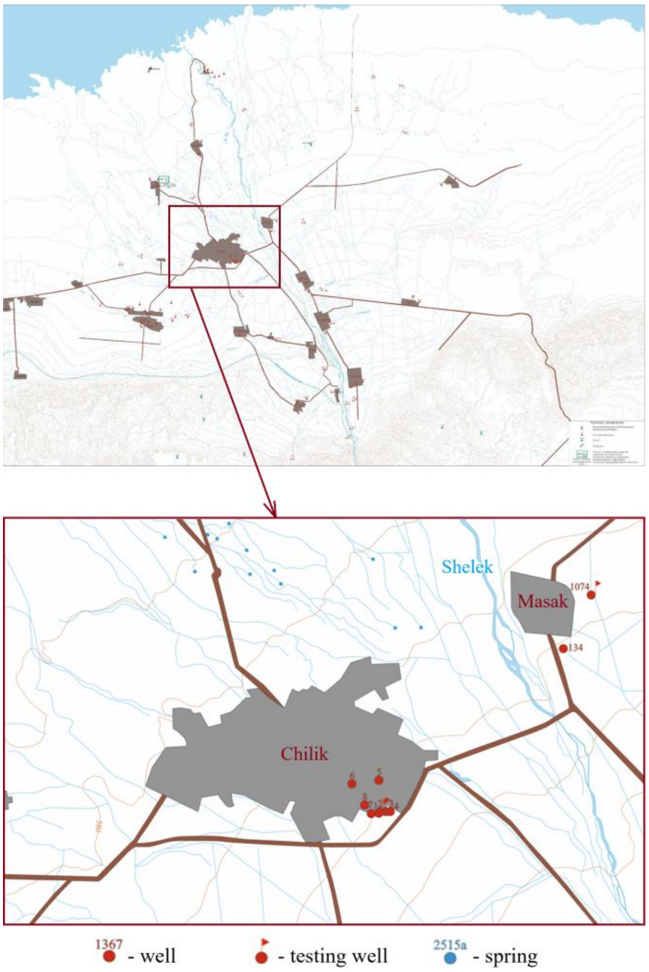

Figure 1. Maps of actual material of Chilik groundwater deposit

The Chilik's flow is primarily fed by glacial and snowmelt. Peak discharge occurs in the spring-summer period (May-July), coinciding with intensive agricultural water use. Mean annual discharge ranges between 38 and 42 m^3/s, yielding an annual runoff volume of about 1.2-1.3 km^3 [18]. Mineralization is low especially in the upper reaches making the water suitable for drinking, household, and irrigation needs [19].

The Chilik River is a key water source for irrigated agriculture in the Chilik Valley, particularly the Shelek Oasis. Water is supplied via an extensive irrigation network, including the main Chilik Canal [20]. Major crops include maize, vegetables, fodder crops (alfalfa), as well as fruit orchards and greenhouse farming [21]. Settlements such as Shelek, Enbek, and Bayseit depend heavily on the river for their livelihoods.

To evaluate the economic efficiency of a hypothetical Managed Aquifer Recharge (MAR) project in the Chilik Basin, we adopted indicative parameters based on empirical data, regional analogies, and international methodologies proposed by Ross [13], Maliva (2014) [2], and Halytsia et al. (2022) [15].

An investment of USD 500000 covers design, geotechnical surveys, construction of infiltration fields, intake channels, pumping stations, and filtration facilities. This estimate aligns with typical MAR project costs in regions with comparable hydro-climatic conditions. Annual operating expenses are set at USD 20000, covering energy, maintenance, staffing, and routine water-quality monitoring. Such figures are corroborated by data from rural water-supply projects and regional irrigation modernization programs in Kazakhstan.

The project assumes 350000 m^3/year of recharge. This is based on spring flood runoff in the Chilik, of which at least 0.5% can be sustainably diverted for infiltration effectively utilizing surplus surface water while minimizing evaporation and downstream losses.

Total annual benefits are estimated at USD 122500, using a tariff of USD 0.35/m^3. This figure reflects not only the market value of drinking water but also indirect benefits: reduced water shortages, improved quality, enhanced agricultural resilience, and ecosystem services (soil degradation prevention). A discount rate of 5% recommended by the European Commission for water-resource projects with a 30-year planning horizon is applied. These parameters follow international cost-benefit analysis standards and are widely used in GIZ, UNDP, and EU Green Deal-supported projects.

4. Results and discussion

Hypothetical efficiency calculation of a MAR system in Almaty region (Chilik River basin) using Ross methodology [14] represented on Table 1.

Table 1. Input conditions (hypothetical MAR project on the Chilik River)

Parameter	Source/Notes
Capital expenditure (C_{cap}), USD	Infiltration fields, intake structures, filtration setup [14]
Annual operating expenditure (C_{op}), USD	Pump maintenance, power, staffing, monitoring
Annual recharge volume (V_{annual}), m^3	Spring flood runoff; 0.5% of ~70-80 million m^3 seasonal flow
Annual economic benefit (B_{annual}), USD	350 000 m^3 × USD 0.35/m^3 + ecosystem services
Discount rate (r), %	Standard for long-term water projects (EU Commission)
Project lifetime (n), years	Typical lifespan of water-infrastructure [15]

Calculation of capital recovery factor (CRF):

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1}. \quad (1)$$

This factor annualizes the capital cost over the project lifetime. After substituting the parameters, the calculated value is $CRF \approx 0.065$, which means that about 6.5% of the capital investment is recovered annually over the project lifetime.

Levelised cost of water (LCW):

$$LCW = \frac{C_{cap} \cdot CRF + C_{op}}{(V_{annual})}. \quad (2)$$

Based on these parameters, the levelised cost of water equals $LCW \approx 0.15$ USD per m^3, which represents the average cost of recharging or producing one cubic meter of water over the project's lifetime.

Benefit-cost ratio (BCR):

$$BCR = \frac{B_{annual}}{\left(C_{cap} \cdot CRF \cdot C_{op}\right)}. \quad (3)$$

The resulting value is $BCR \approx 2.0$, which means that the annual economic benefits are approximately twice the annualized costs. Economic Conclusion: $BCR > 1$ indicates the MAR project is economically viable and sustainable under these assumptions.

The project provides several additional advantages. It effectively utilizes spring floodwater that would otherwise be lost through runoff, thereby improving the overall efficiency of water resource management. At the same time, it enhances groundwater quality through the process of natural filtration as the recharged water percolates through soil and aquifer layers. The system also strengthens agricultural resilience, as it reduces farmers' dependence on irregular surface water supplies and mitigates the risks associated with seasonal droughts. Finally, the project creates opportunities for research and education, encouraging collaboration with local colleges and research institutes in studying and improving Managed Aquifer Recharge (MAR) technologies.

Table 2. Justification of parameter estimates

Parameter	Value	Justification / source
Capital expenditure, USD	500000	Typical cost for infiltration-field construction, intakes, and pipelines; comparable to GIZ Central Asia and India cases [14, 15]
Operating expenditure, USD/year	20000	Includes power, staffing, pump and filter maintenance; aligns with rural water-supply budgets in Kapchagay & Turkestan regions
Annual recharge volume, m^3	350000	0.5% of spring runoff (10-15 m^3/s over 60 days ≈ 7-80 million m^3)
Annual economic benefit, USD	122500	Based on USD 0.30-0.35/m^3 local tariff plus 5-10% bonus for ecosystem and social benefits
Discount rate, %	5	In line with EU Commission, GIZ, and UNDP cost-benefit analysis standards
Project lifetime, years	30	Standard life cycle for water and geotechnical infrastructure

For the efficiency calculation of the hypothetical MAR system in Almaty Region (Chilik River basin), we used parameters based on international best practice and adapted to the Kazakh context. A capital investment of USD 500000 reflects the average cost of constructing infiltration facilities including geotechnical surveys, earthworks, and connection to the existing water supply network and is comparable to similar projects in India, Poland, and Central Asia (GIZ) [13, 15]. Annual operating expenses of USD 20000 cover electricity consumption, equipment depreciation, operator salaries, and periodic monitoring. Similar figures appear in the budgets of Kazakh water-supply projects in the southern regions (Kapchagay, Turkestan Region).

The annual recharge volume is assumed to be 350000 m^3/year, based on estimates of spring floodflows in the Chilik River which average 10-15 m^3/s over two months. Even diverting just 0.5% of this resource makes MAR implementation feasible.

Economic benefit is calculated using the local drinking-water tariff (≈ 0.30-0.35 USD/m^3) plus an allowance for quality and reliability improvements. The analysis also applies the European Commission's recommended 5% discount rate and a standard 30-year infrastructure lifespan.

A comparative analysis highlighted both the advantages and the current limitations of various MAR implementation models in Kazakhstan, the USA, and Europe. Global experience demonstrates MAR's high economic efficiency in agriculture and its resilience to climate-driven risks.

Kazakhstan's Potential and Local Case Studies Modeling and field studies indicate that Kazakhstan has significant potential for MAR, especially in arid zones and areas with pronounced seasonal water imbalances. A regional study in the Zhambyl Region identified soils and hydrogeological conditions highly favorable to large-scale MAR deployment.

The next research step involves conducting field measurements of flow rates and water quality in the Chilik River basin. These data will make it possible to transition from hypothetical estimates to a calibrated economic efficiency model for the Managed Aquifer Recharge (MAR) system. The planned activities include measuring seasonal discharge variations in cubic meters per second, assessing the suitability of floodwater for infiltration based on its chemical composition and turbidity, and characterizing the aquifer properties in potential recharge zones to ensure accurate modeling and practical applicability.

Collecting such empirical data will make it possible to perform a correlation analysis between natural variables such as spring runoff volume, flood duration, and mineralization levels and the modeled economic indicators, including the levelised cost, benefit-cost ratio, and discounted returns. This approach not only enhances the accuracy of the assessment but also adapts the model to the specific hydrogeological conditions of the basin. Consequently, real hydrometric data from the Chilik River will provide a solid foundation for validating the proposed MAR model, refining water availability estimates, reducing uncertainty, and identifying the main factors that determine project profitability. Given the climatic and hydrological variability of the region, this method ensures both scientific rigor and practical applicability of the MAR economic model for the Almaty Region and other areas with similar conditions.

The study will also investigate how integrating Managed Aquifer Recharge (MAR) systems with terrain-based digital elevation models (DEMs) and field data can optimize water capture and underground storage, reduce flood risks, and enhance overall climate resilience. The primary goal of the project is to develop practical solutions for sustainable water-resource management in Kazakhstan's semi-arid regions, where seasonal water scarcity and climate variability create significant challenges. By drawing on international MAR case studies from Spain to Australia the research aims to formulate evidence-based recommendations for adapting and scaling MAR technologies across Kazakhstan and the broader Central Asian region.

5. Conclusions

The hypothetical analysis of the economic efficiency of implementing a Managed Aquifer Recharge (MAR) system in the Chilik River basin shows that such projects have high potential for profitability and resilience under the conditions of Kazakhstan's southern regions. The calculated parameters, based on international methodologies and adapted to local conditions, indicate a cost level comparable to MAR projects carried out abroad, while the economic benefit expressed through drinking-water tariffs and additional ecosystem services yields a benefit-cost ratio (BCR) greater than 2.0, confirming the project's viability.

Using spring floodwaters as the infiltration source allows the surplus surface water to be managed efficiently, reducing losses from evaporation and runoff. At the same time, the project helps improve groundwater quality through natural filtration and strengthens water security and agricultural sector resilience.

Despite the hypothetical nature of the current assessment, the proposed methodology demonstrates the applicability of MAR systems to the Almaty Region's conditions. The next step should be to conduct field measurements of hydrological and geological parameters to refine the model's inputs, calibrate its outputs, and prepare a detailed techno-economic feasibility study based on actual data.

In this way, MAR technology represents a promising tool for sustainable water-resource management amid climate variability and growing water scarcity. If a pilot project in the Chilik River basin proves successful, this model could be scaled up and adapted to other regions of Kazakhstan with similar natural conditions.

Author contributions

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

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

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

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Жер асты қабаттарында тасқын суларын жинау арқылы Қазақстанның су бюджетін оңтайландыру

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Аңдатпа. Зерттеу климаттың өзгеруі мен су тапшылығы жағдайында тұрақты сумен жабдықтау әдісі ретінде басқарылатын Сулы горизонтты толықтыру жүйелерінің (managed Aquifer Recharge, MAR) экономикалық тиімділігін талдауға бағытталған. Жұмыста MAR негізгі принциптері, оның сумен жабдықтау шығындарын азайтудағы, су шығынын азайтудағы, экстремалды климаттық жағдайларға төзімділікті арттырудағы және экожүйелердің тепе-теңдігін сақтаудағы артықшылықтары қарастырылады. MAR қолдану ауыл шаруашылығы мен жергілікті қауымдастықтарға бере алатын экономикалық және әлеуметтік артықшылықтарға ерекше назар аударылады. Зерттеу әдістемесі қолданыстағы тәжірибені талдауды, экономикалық модельдеуді және аймақтық деңгейде MAR технологиясын енгізудің әсерін бағалауды қамтиды. Нәтижелер MAR су ресурстарын тұрақты пайдалануға және өмір сүру сапасын жақсартуға ықпал ететін тиімді және үнемді су стратегиясы екенін көрсетеді. Ғылыми жаңалық- климаттың өзгеруі жағдайында MAR жүйелерін қолданудың экономикалық орындылығын негіздеу, ал зерттеудің практикалық маңыздылығы - алынған нәтижелерді су ресурстарын басқару тәжірибесіне енгізу мүмкіндігінде жатыр.

Негізгі сөздер: *басқарылатын су өткізгіш қабаттарды қайта толтыру, экономикалық тиімділік, су жабдықтау, климат өзгерісі, су ресурстары, тұрақты даму.*

Оптимизация водного бюджета Казахстана за счёт накопления паводковых вод в подпочвенных горизонтах

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Аннотация. Исследование посвящено анализу экономической эффективности систем управляемого пополнения водоносных горизонтов (Managed Aquifer Recharge, MAR) как метода устойчивого водоснабжения в условиях изменения климата и нехватки водных ресурсов. В работе рассматриваются основные принципы MAR, его преимущества в снижении затрат на водоснабжение, минимизации потерь воды, повышении устойчивости к экстремальным климатическим условиям и поддержании баланса экосистем. Особое внимание уделено экономическим и социальным выгодам, которые применение MAR может предоставить сельскому хозяйству и местным сообществам. Методология исследования включает анализ существующей практики, экономическое моделирование и оценку влияния внедрения технологий MAR на региональном уровне. Результаты демонстрируют, что MAR является эффективной и экономически выгодной стратегией водоснабжения, способствующей устойчивому использованию водных ресурсов и повышению качества жизни. Научная новизна заключается в обосновании экономической целесообразности применения систем MAR в контексте изменения климата, а практическая значимость исследования – в возможности внедрения полученных результатов в практику управления водными ресурсами.

Ключевые слова: *управляемое пополнение водоносных горизонтов, экономическая эффективность, водоснабжение, изменение климата, водные ресурсы, устойчивое развитие.*

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