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Mapping the potential for managed aquifer recharge in Kazakhstan

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ABSTRACT

MAR remains relatively underutilized in Central Asia despite its potential to address water scarcity issues, particularly those related to seasonal fluctuations in water availability. Thus, the objective of this study was to produce a map depicting the potential suitability of managed aquifer recharge (MAR) implementation in Kazakhstan. Employing a multi-criteria decision analysis framework, five distinct physical criteria were integrated and visualized within a Geographic Information System (GIS) to delineate the intrinsic potential for MAR. To demonstrate the practical utility of the generated map, it was applied to the Zhambyl region in Southern Kazakhstan, an area previously afflicted by water scarcity challenges. The intrinsic MAR potential map was overlaid with remote sensing data identifying potential water sources and water utilization patterns. This overlay facilitated the identification of priority areas with potential for further evaluation for MAR implementation. The map developed for Kazakhstan represents the first spatial representation of MAR potential within the region, serving to raise awareness regarding the feasibility of MAR application. It is anticipated that dissemination of this map will enhance understanding among water management professionals, potentially catalysing the integration of MAR methodologies into regional water management strategies.

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1. Introduction

Kazakhstan is located in semi-arid and arid climate zones of Central Asia, which are considered highly vulnerable to climate change (Kaliyeva et al., 2021). Climate projections forecast an above-the-global-mean temperature increase along with increased heatwave frequencies and intense weather events (Muccione & Fiddes, 2019). The projected temperature increase could accelerate glacier melt and lead to shorter, more intense snow melt seasons, which would result in an increase in river flow and spring flood risk (World Bank Group & Asian Development Bank, 2021). The water released during snowmelt can account for 50-80% of the annual runoff in river basins of colder climates and cause severe floods and economic damage (Gelfan & Motovilov, 2009).

Kazakhstan's agriculture in southern regions heavily relies on irrigation, which accounts for 65% of Kazakhstan's freshwater use (Dmitryuk, 2020). Its government plans to increase the irrigated areas from 1.6 million ha in 2021 to 3 million ha by 2030 (primeminister.kz, 2021) resulting in even higher agricultural water demands. At present, mainly surface water storage and irrigation channels are utilized to meet the irrigational water demand (Anzai et al., 2014; Karimov et al., 2015).

While most water in Kazakhstan is available during times of lower demand (e.g. during spring snowmelt) and stored in snowpack, its peak water demand is during summer, when precipitation cannot meet the plant water demand. This calls for an intermediate storage of water to alter these shifts in water supply and demand. Currently, this storage is realized as surface water reservoirs.

Surface water storage is characterized by a lot of challenges, such as evaporation losses, increased potential for water pollution, high demand in available land or high economic costs and public opposition (Dillon, 2012). In order to surpass these disadvantages, measures to store water in the subsurface have been becoming increasingly popular. The use of void space in aquifers for water storage by intentionally recharging the aquifer through wells, water spreading or waterbed channel modifications is called managed aquifer recharge (MAR). MAR schemes are increasingly implemented worldwide with the recharged volume increasing at a rate of 5%/year since the 1960s (Dillon et al., 2019). Concerning Kazakhstan, MAR could be particularly beneficial in enabling the storage of surplus water in times of high availability and subsequent recovery during times of high demand.

As MAR comprises a variety of possible solutions (Dillon, 2005), the most common MAR techniques are surface spreading methods, such as infiltration basins or furrows and off-season flooding of agricultural areas (Stefan & Ansems, 2018). In general, these methods have lesser technical requirements, are less costly to implement than recharge wells but require larger area of land. As land availability is given in Kazakhstan, they comprise a possible solution. They are further advantageous, if a lot of water is available for recharge during a short duration, which would be the case for meltwater in spring in Kazakhstan.

These methods can even be enhanced to account for Kazakhstan’s cold climate. Water resources are naturally stored in the form of snowpack and ice during winter, when less water is needed. Supported by some technical measures, this water could be stored to be available during the drier seasons. Icing can be enhanced by triggering aufeis progression through discharging surplus water on existing ice blocks, e.g. on lakes or drainage channels (Narantsogt & Mohrlok, 2019). Infiltration basins can be operated during winter, with continuous inflow preventing the freezing of the deeper water layers (Tanttu & Jokela, 2018). Van Houtte & Verbauwhede (2021) suggested subterranean infiltration methods such as shallow vadose zone wells, which could surpass the upper frozen soil layers for recharging.

Thus far, only modeling and field test studies have been reported as application for MAR in Kazakhstan. Karimov et al. (2015) analysed the potential for MAR in the Syrdarya river basin, as an alternative to in-channel reservoirs. Mirlas et al. (2021) conducted a modeling and field study to assess the use of the existing subsurface drainage in Ile River basin in South-East Kazakhstan for artificial groundwater recharge. In further studies, Mirlas et al. (2015) evaluated the potential for groundwater recharge using infiltration pools in the Karatal agricultural area as well as the use of constructed mini pools at the Aksu area (South-East Kazakhstan) (Mirlas et al., 2022). Teleubay et al. (2023) have identified farm pond sites for spring meltwater collection using the GIS-based analytical hierarchy process for the steppe region of North Kazakhstan. However, their approach focused on surface storage of snowmelt water, while MAR focuses on subsurface storage. Particularly in dry regions, the subsurface storage of water should be preferred over surface ponds to counteract evaporation losses.

MAR has found little application in Kazakhstan yet, even though it is a concept that has been applied in similar climates, e.g. in Northern China (Guo et al. 2022), in Finland and Central USA (Zheng et al. 2021). There needs to be an initiative to make the concept more known in the region and to show its potential for Kazakh water management. MAR potential mapping is a key element in advocating for an increased implementation of MAR (Sallwey et al., 2018). These maps can even be integrated into the strategic decision-making for water management as it was shown in the recharge master plan of South Africa (Murray et al., 2007). Overall, MAR maps can be an easy to understand and visibly appealing means to advocate for MAR solutions as a sustainable water management practice (De Winaar et al. 2007, Agarwal et al. 2013, Saidi et al. 2017). As to the authors’ knowledge, no MAR potential map has been published for Kazakhstan.

The aim of this paper is therefore to compile a MAR potential map for Kazakhstan combining information on soil, hydrogeology and land use with the help of geographic information systems (GIS). The resulting map is further used in the exemplary Zhambyl region in Southern Kazakhstan, to show how the combination of the MAR potential map with information on water source and demand can be used to create a showcase on MAR applicability at regional level. The overall intention by creating a MAR potential map for Kazakhstan is to help to raise awareness about MAR as a promising potential solution for sustainable water management in Kazakhstan.

2. Materials and Methods

2.1. Geographic Information System Multi-Criteria Decision Analysis (GIS-MCDA)

Spatial decision-making involves selecting the most suitable locations or alternatives from a set of options based on multiple criteria. GIS-based Multi-Criteria Decision Analysis (GIS-MCDA) is an integrative approach that combines GIS mapping with decision-making techniques to evaluate, rank, and visualize alternatives in order to make complex spatial decisions (Malczewski & Rinner, 2015).

To begin, a set of criteria is defined that represents different factors influencing the decision (Malczewski, 1999). Geographic data layers are created or obtained to represent each criterion spatially. In this study, the decision problem is defined by depicting those areas in Kazakhstan that have a high intrinsic potential for MAR application.

A common scale for the criteria is achieved by standardization through stepwise and linear functions. The alternatives that each criterion contain are further scored based on their performance with respect to the decision problem.

Decision-makers assign weights to each criterion, reflecting their relative importance for the decision problem. Weights are usually based on expert knowledge, stakeholder preferences, or analytical methods, with Pairwise Comparison being the most commonly used methodology (Sallwey et al., 2018). While the method is relatively more complex than other methods, it gives a more sophisticated background to the decision-making process and enables the verification of the consistency of the assigned weights. This is managed by computing the consistency ratio, which is an indicator of the consistency of the pairwise judgement of the criteria. Thus, it is a reference factor for the goodness of the decision-maker's judgement. The assignment of weights is based on the pairwise matrix by Saaty (1980) that is created by rating the preference of a pair of criteria among each other. The decision maker has to state whether two criteria are of the same importance or whether there is a preference for one of them and how strong the preference is. Forming the comparison matrix, these criteria preferences are then divided by the column total, which computes a matrix of relative weights. The relative weights are averaged per column (ergo per criterion) and form the final weights of each criterion.

The individual scores for each criterion are combined through the decision rule. Criteria and weights are combined to calculate an overall suitability index. Weighted linear combination is the most commonly used decision rule (Sallwey et al., 2018). The score of a site is obtained by summing up all the products of the standardized criteria maps multiplied by their respective weights (Eq. 1).

$$A_i = \sum_{j=1}^{n} w_j x_{ij} \qquad \text{(Eq. 1)}$$

Where A_i is the weighted linear combination score or index, n is the total number of criteria, x_{ij}=score of the i-th alternative with respect to the j-th criterion and w_j= normalized weight of criterion.

The development of web-tools have made the GIS-MCDA methodology easily accessible and further offer an open-access space for the publication of MAR potential maps (Sallwey et al., 2019). The reclassified criteria maps as well as the resulting suitability map were uploaded to the INOWAS toolbox for GIS suitability mapping. The maps can be accessed upon registration under https://dss.inowas.com/tools (T05: GIS multi-criteria decision analysis —Kazakhstan MAR potential map).

2.2. Criteria selection and GIS Data used

One of the most essential steps in GIS-MCDA is the selection of appropriate criteria. In this study, a two-step approach is conducted, where, at first, an intrinsic map is created as a reference map depicting the intrinsic MAR potential of Kazakhstan. The intrinsic map can be seen as a basis to be overlain with further maps to depict water sources and water demand. As water sources and demand can differ depending on the region of interest and are criteria that can change quickly over time, we decided to keep these separate from the intrinsic map.

In this study, five criteria were selected to create the intrinsic MAR suitability map. They depict the potential for MAR, based on the natural criteria: slope, land cover, geology, soil type and soil salinity (Table I). These criteria were chosen based on criteria used in other MAR potential studies with similar conditions according to the review from Sallwey et al. (2018). Ideally, more information about the groundwater situation in Kazakhstan should be included into the study, e.g information on groundwater level fluctuation or the thickness or transmissivity of the aquifer. This information was neither publicly available, nor in other ways accessible to the authors of this study.

While the intrinsic potential shows the feasibility of MAR application, the actual implementation of MAR is dependent on a potential water source and the local water demand. Thus, in the second step, the intrinsic map will be overlain by a map showing the distance to surface water bodies to depict the potential water source for MAR integration and by a map showing the distance to agricultural areas as they represent the potential users of water stored through MAR.

Consequently, the final MAR feasibility score was determined by combining the intrinsic map with maps of the water source and the water demand. This was done following the scheme:

$$Finalscore = \frac{1}{3} * intrinsic\ potential + \frac{1}{3} * water\ source + \frac{1}{3} * water\ demand \quad \text{(Eq. 2)}$$

We decided to weight the intrinsic potential, the water demand and the water source equally, as all three are important drivers that foster the application of a MAR project and neither can be disregarded when looking into MAR application. Nevertheless, depending on national policies, future development, climate impact etc., the ratio can be adapted for future studies to reflect these influences, especially at regional scale.

Table I. Thematic maps used for the study, including web source

Map	Source	Website
Digital elevation model	MERIT DEM	http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/index.html
Land cover	ESRI	https://livingatlas.arcgis.com/landcover/
Geology	JRC	Huscroft et al. 2018
Soil Texture	FAO	https://www.fao.org/
Soil salinity	FAO	https://data.apps.fao.org/glosis/
Water bodies of Kazakhstan	ESRI	Extracted from https://livingatlas.arcgis.com/landcover/

2.2.1. Slope

The slope was calculated from the MERIT DEM (Raster resolution 77 m) by using the QGIS tool GDAL-slope (Figure 1). The calculated slope ranges from 0 to 88° with most of Kazakhstan being relatively flat (80% with slope less than 1.4°). Only the mountainous regions in the East and Southeast have slopes higher than 30° (0.4% of the area). For the implementation of MAR schemes, flat terrain is generally advantageous and slopes of less than 5° are considered the most suitable (94% of total land) (Riad et al., 2011; Shankar & Mohan, 2005; Zaidi et al., 2015). Higher slopes are linked to steeper groundwater gradients. Thus, the higher the slope, the less efficient is the recovery of the water infiltrated, as the water will be less available at the site.

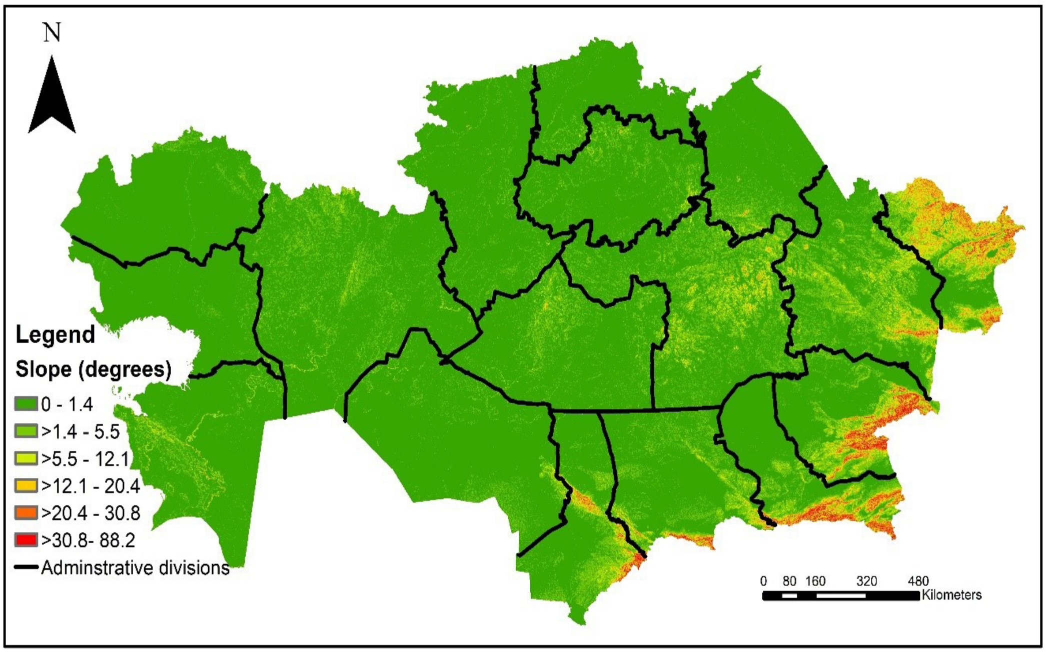

Figure 1. Map of slope distribution in Kazakhstan

2.2.2. Land cover

The land cover map (Raster resolution 10 m) differentiates nine different land use types for Kazakhstan: water, forest, flooded vegetation, crops, built areas, bare ground, permanent snow/ice, rangeland and clouds (Figure 2). The majority of the land is classified as rangeland (83.3%), followed by crops (6.1%) particularly in Northern and Southern Kazakhstan and bare ground (5.7%) in the Western part of the country. All other land use types make up the remaining 5% of the country. In terms of MAR implementation, the most suitable land use types are open spaces (without vegetation or buildings), such as rangeland and bare ground (Ghayoumian et al., 2007; Shankar & Mohan, 2005). They provide sufficient construction space and generally have no conflicting other utilization.

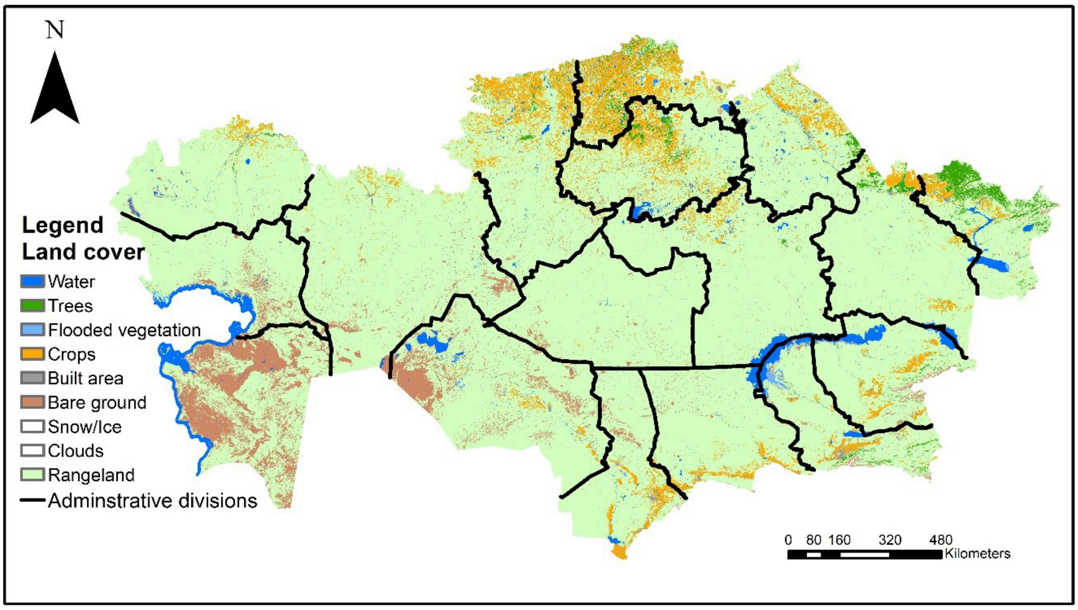

Figure 2. Map of land cover distribution in Kazakhstan

2.2.3. Geology

For the geology, the GLHYMPS 2.0 dataset (Huscroft et al., 2018) was used. Among others, the dataset contains information on the hydraulic conductivity of the geological features. This data was used in -log (k) (cm/s) format which can be interpreted according to (Bear, 1972). For groundwater recharge, a higher hydraulic conductivity is advantageous as water can distribute quicker along the geologic formation allowing for higher volumes of water to be recharged.

Overall, two thirds of the country's area is described to have a hydraulic conductivity higher than 4 cm/s. These areas are mostly in Western, Northern and Central Kazakhstan (Figure 3). Small parts of Central and Northern Kazakhstan fall into the category of the lowest hydraulic conductivity. They make up 4% of the area. Most of the geology features of Southern and Eastern Kazakhstan have semipervious materials (38 % of the area). It should be noted that no hydrogeological information was available for a small area (less than 0.003%).

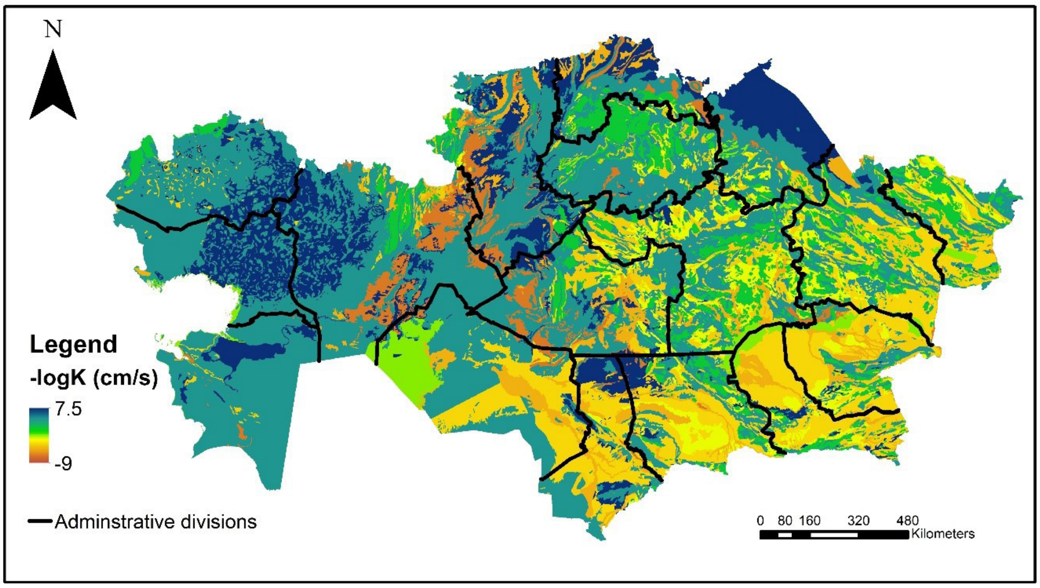

Figure 3. Map of hydraulic conductivity (in –logK cm/s) of the geologic features of Kazakhstan

2.2.4. Soil texture

The soil texture map shows ten different soil types that are distributed in Kazakhstan (Figure 4). The most common soil types are loam (44.9% of the area) and clay loam (19.6% of the area), which are very evenly distributed over the country. Larger areas with more pervious soil types (sandy loam and loamy sand) can be found in the Northeast, the West and the Central Southeast of the country.

For MAR application, soil types with coarser grains are more suitable than finer materials, as the water can infiltrate faster into soils with bigger grains and pore spaces. In terms of MAR suitability, higher infiltration rates enable the recharge of a larger volume of water (Bonilla Valverde et al., 2016; Zaidi et al., 2015).

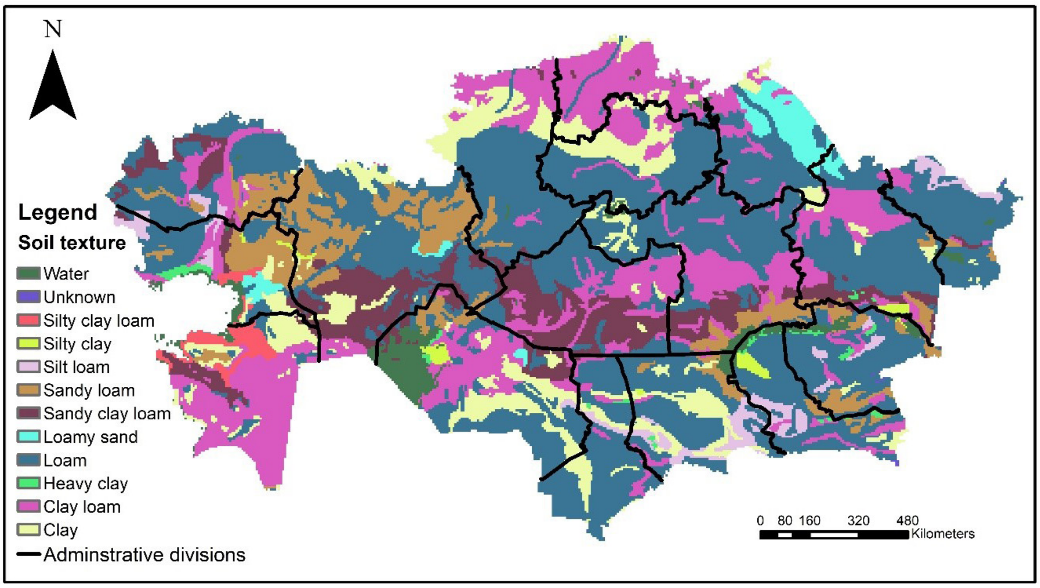

Figure 4. Map of soil texture distribution in Kazakhstan

2.2.5. Soil salinity

The soil salinity influences the recharge of aquifers both in quantitative and qualitative ways. Increased salt concentrations lead to degradation of the soil structure and decreased infiltration capacity (FAO, 2021). It further enriches the concentration of minerals in the percolating water, leading to higher salt concentrations in the aquifer. Thus, less saline soils are more suitable for managed aquifer recharge (Anane et al., 2008; Gdoura et al., 2015).

The map (Raster resolution 1 km) contains five categories for sodicity hazard with corresponding values on the electrical conductivity of the saturated paste extract (ECe), which has been the preferred index for soil salinity (Figure 5). The categories for sodicity hazard are none (EC < 0.75 dS/m), slight (EC 0.75-2 dS/m), moderate (EC 2-4 dS/m), strong (EC 4-8 dS/m) and very strong (EC 8-15 dS/m).

As can be seen, most of the soil coverage are expected to have no salinization (83% of the country). The West, South and South-eastern parts of the country show a slight salinization, 14.8% of Kazakhstan falls into this category. High salinization hotspots are observed in the South-eastern part of the state (0.3% of the country).

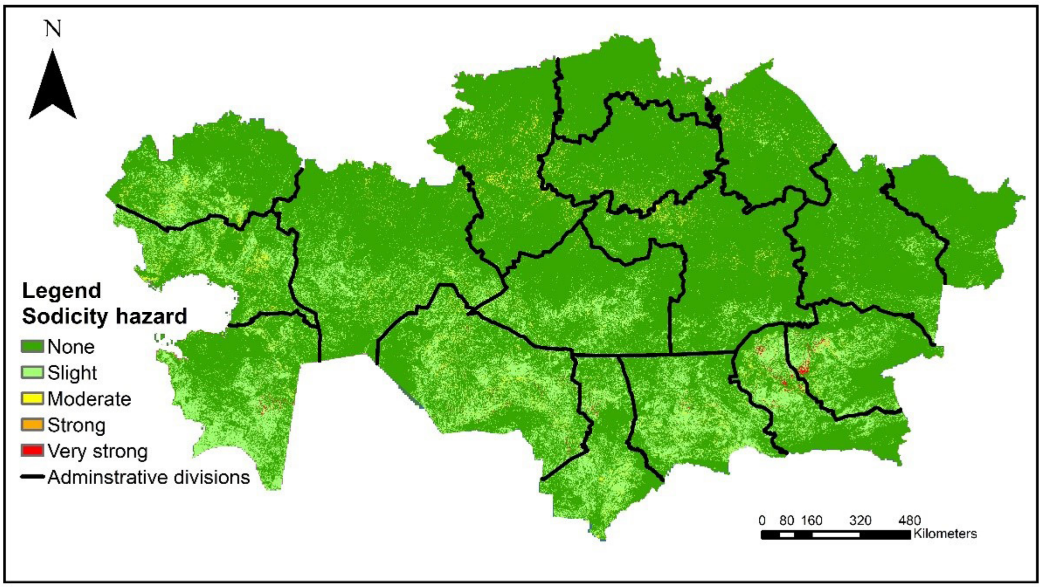

Figure 5. Map of soil salinity distribution in Kazakhstan

3. Results

3.1. Criteria standardization and weighting

To combine the criteria, they need be standardized and put on a common scale. For this study, a classification scheme from 1 to 5 was chosen with 5 being most suitable for MAR application, 4 being more suitable, 3 being moderately suitable, 2 being less suitable and 1 least suitable for MAR application. Each criterion was standardized and reclassified according to Table II. The criterion classes were chosen based on the GIS-MCDA studies mentioned in the sections 2.2.1.-2.2.5 that use the same criteria. Further information on criteria classification was taken from database query tool for GIS-based MAR suitability mapping (Sallwey et al., 2019). The resulting reclassified maps are available in the attachments (Appendix A1).

Table II. Standardization of used criteria

Criterion	Criterion class	Standardization
Land use	Rangeland	5
	Bare ground, crops	4
	Flooded vegetation	3
	Forest	2
	Water, Built areas, Snow/Ice, Clouds	1
Slope (in °)	0 - 1.5	5
	> 1.5 - 3	4
	> 3 - 6	3
	> 6 - 12	2
	> 12	1
Geology (in –log K (cm/s))	0 - 2	5
	> 2 - 4	4
	> 4 - 6	3
	> 6 - 8	2
	> 8	1
Soil type	Loamy sand	5
	Sandy loam	4
	Clay loam, Loam, Sandy clay loam	3
	Silty loam, Silty clay loam	2
	Clay, Heavy clay, Silty clay, Unknown, Water	1
Soil salinity/ Sodicity hazard	None (EC < 0.75 dS/m)	5
	Slight (EC 0.75-2 dS/m)	4
	Moderate (EC 2-4 dS/m)	3
	High (EC 4-8 dS/m)	2
	Extreme (EC 8-15 dS/m)	1

To combine the reclassified maps, they need to be weighted according to their importance for the determination of MAR potential. Pairwise comparison was used as the method to determine the weight of each criterion. Each criterion is rated in a pairwise comparison with regard to a second criterion. The method was applied through the INOWAS platform (Sallwey et al., 2019), where a slider is moved towards the more important criterion with the distance from the centre determining the magnitude of higher importance (Figure 6). The resulting weights are calculated with geology being the most important criterion (43%) and land use being the least important (7.6%). Additionally, the tool calculated the consistency ration, which indicated whether the ten choices of criterion importance are consistent with each other.

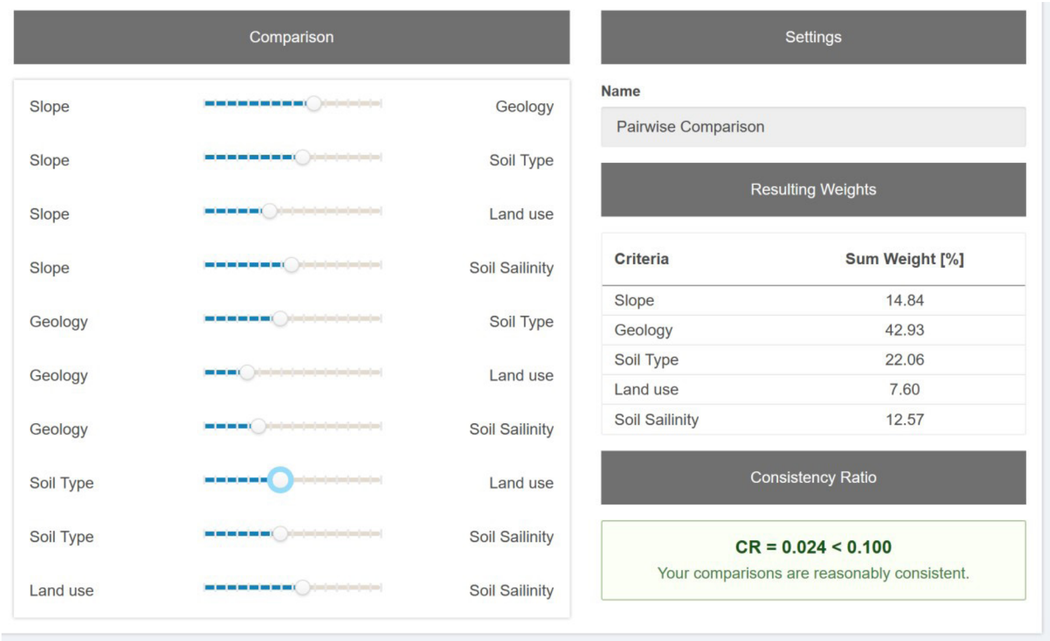

Figure 6. Criteria weighting with pairwise comparison method on the INOWAS platform. The more the slider is moved towards a criterion, the stronger is the preference towards this criterion in comparison to the second criterion of the pair.

3.2. Intrinsic MAR potential map

The final map of intrinsic MAR potential was calculated through combining the reclassified criteria and the weights determined in section 3.1. The final map (Figure 7) shows an index for the potential reaching from 1 to 5. The higher the number, the higher the MAR potential.

There are very little areas that fall into the category with the least potential (less than 0.01 % of the area). They are located in the highest mountainous regions and characterized by steep slopes and unsuitable land use types. Larger areas with the highest potential (19.6 % of the area) can be found in the southern, as well as the central regions of Kazakhstan, which can be attributed to its suitable geological conditions as well as the flat rangelands that are widely common in the region.

In general, the intrinsic potential for MAR application is given in wide areas of Kazakhstan. The country is characterized by even rangeland with little soil salinization. The soil type is a limiting factor, as loamy and clayey soils are very common. The hydraulic conductivity of the subsurface is heterogeneously distributed, which determines to areas from high potential from those with medium potential.

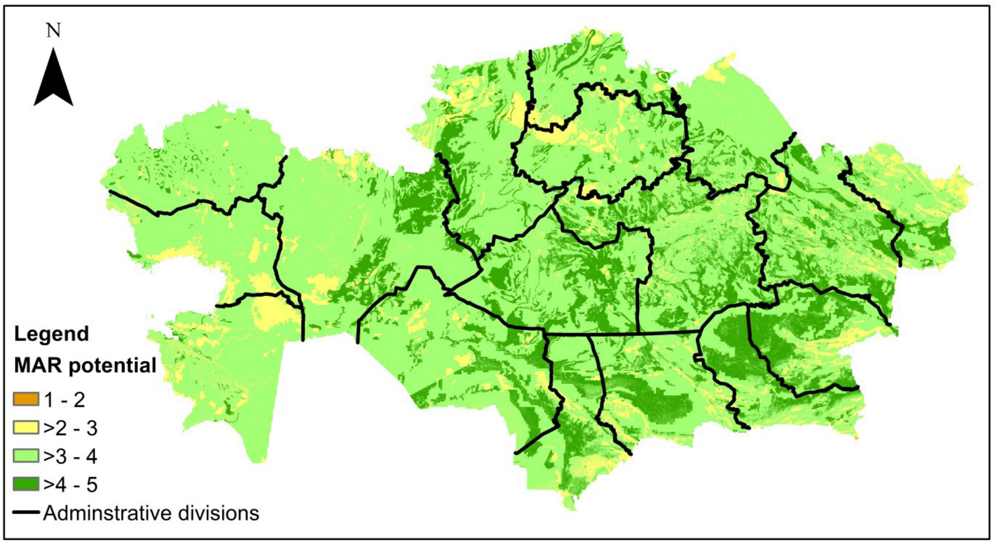

Figure 7. Intrinsic map of MAR potential for Kazakhstan with an index rating from 1 to 5

3.3. Application of intrinsic map for Zhambyl area

While Figure 7 shows the MAR potential for all of Kazakhstan, the application of MAR is not practical in large parts of the country, as they are sparsely inhabited steppe regions. Next to the intrinsic potential, which is determined by physical characteristics, the feasibility of MAR application is determined by availability of a water resource that can be used for MAR, e.g. collected stormwater or river water. The second factor determining the feasibility of application is the demand. Groundwater could be recharged to fulfil the growing water demand of irrigated agriculture that has its peak water demand during growth season, which is a time that is typically accompanied with lesser and irregular rainfall.

To display how the intrinsic MAR map could be used further, Zhambyl region was selected as an exemplary region for further MAR analysis. Zhambyl region is located in the southern part of Kazakhstan and has a total area of 144263 km^2 (Figure 8). The average annual precipitation for the region constitutes 250 mm (Aldazhanova et al., 2022). According to Beck et al.'s (2018) dataset the main climate zones are: BWk (Arid, desert, cold) and BSk (Arid, steppe, cold). The main land use types are: Pasture lands (94144 km^2), Arable land (8365 km^2), Hayfields (2273 km^2) (Aldazhanova et al. 2022). The main water sources for irrigation are rivers Shu, Talas and Assy. Types of crops grown: grain, maize, sugar beet, vegetables, potatoes, fruit, grapes, melons and oilseeds.

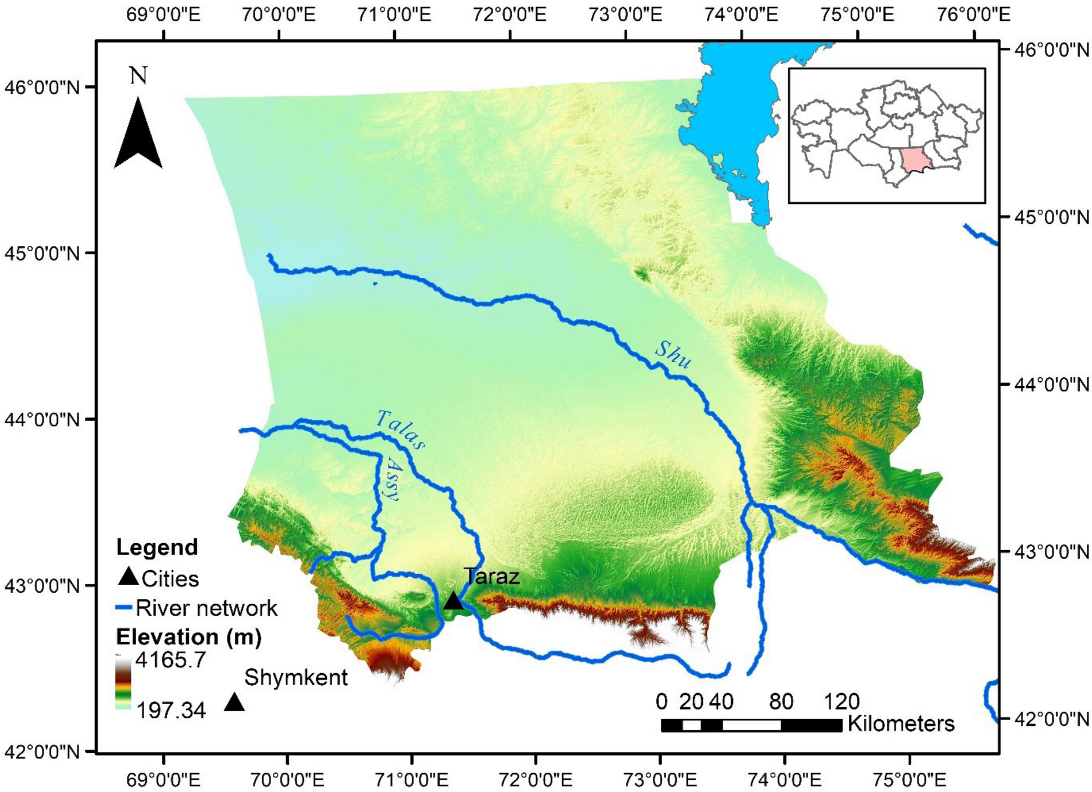

Figure 8. Zhambyl region in Southern Kazakhstan with elevation and river network.

Zhambyl region is located within the large Shu-Sarysu system of artesian basins and has favourable conditions for the formation and accumulation of significant groundwater resources (Beisenova and Aldazhanova 2022). The most promising for agricultural irrigation purposes are groundwaters of alluvial-proluvial Quaternary deposits of cones of removal and foothill plains of Karatau, Kyrgyz Alatau, Shu-Ili mountains, intermountain hollows, as well as alluvial deposits of Shu, Talas, Assa, and Kuragaty river valleys.

Irrigated agriculture in this southern Kazakh region relies primarily on inflow from the transboundary rivers Shu and Talas originating in Kyrgyzstan. In 2023, local farmers experienced a significant water shortage due to the absence of flow from upstream Kyrgyzstan (gov.kz, 2023). This has brought serious loss of agricultural productivity which had to be compensated by the Government. High dependence of local agriculture on transboundary river flow makes it vulnerable to such cases and MAR could be a viable solution to counteract these problems. To investigate the matter, the intrinsic MAR map of Kazakhstan was cropped to the region of Zhambyl (Figure 9 A).

As a potential water source, surface water bodies of the region were analysed. Particularly during spring snowmelt, these water bodies carry large amounts of surplus water that could be stored for later use. Assuming that water has to be transported from the surface water body to the MAR site, a relative proximity to the water body is advantageous as piping and pumps have to be installed the further the recharge site is away. The classification used to obtain the criterion map (Figure 9B) is stated in Table III, with the areas closest to the water body obtaining the highest standardization score. Areas further away than 20 km were deemed unfeasible.

Agricultural lands as a potential water beneficiary were depicted through selecting agricultural areas from the land use map (Figure 2). Since water has to be transferred from the potential MAR site to the agricultural areas, a relative proximity of both was deemed most feasible. The classification of the proximity to the agricultural land is stated in Table III. The standardized map for proximity to agricultural land is shown in Figure 9C.

Table III. Standardization of criteria for water availability and water demand.

Criterion	Criterion class	Standardization
Proximity to the surface water body (km)	<= 1	5
	> 1 - 5	4
	> 5 - 10	3
	> 10 - 20	2
	> 20	0
Proximity to agricultural land (km)	= 0	5
	> 0 - 1	4
	> 1 - 5	3
	> 5 - 10	2
	> 10	0

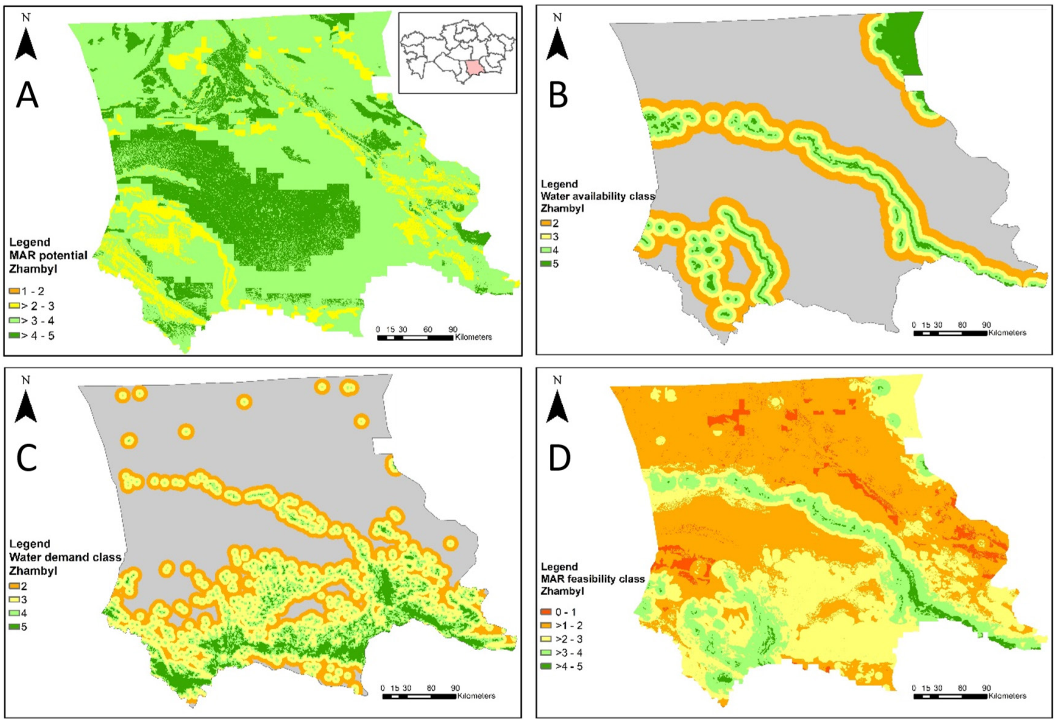

Figure 9. MAR potential map for Zhambyl region showing its intrinsic potential (A), water availability (B), estimated water demand for irrigation(C) as well as combined potential (D)

The resulting map for MAR potential in the Zhambyl region is shown in Figure 9D. With the focus on surface water bodies (mainly rivers Shu and Talas in this region) as well as the existing agricultural areas, the highest MAR potential can be found along river Shu, particularly in its southern section close to the cities Shu and Moiynkum. Further regions with promising potential are along the Talas river in the south-western part of Zhambyl. In both these regions, the intrinsic potential is given as well as availability of water and a defined water demand.

Other regions, such as the Northeast around Lake Balkhash, show a high water availability but lesser intrinsic potential and no (agricultural) water demand. The region in the central south on the other hand, has a high demand for water through agriculture, but no available surface water bodies, which reduces its MAR feasibility, within the constraints given.

4. Discussion and Conclusion

This study shows how an intrinsic MAR potential map for Kazakhstan can be used to identify areas of interest in a selected region. The intrinsic map merges the criteria, such as slope, geology, soil type, land use and soil salinity to identify the regions that present the best physical conditions in Kazakhstan for the application of MAR schemes.

Around 20 % of Kazakhstan shows a high potential for MAR application, with those regions mostly distributed in Southern and Central Kazakhstan. The vast majority of the country has at least medium high potential for MAR application with only the most mountainous region showing the least potential. Kazakhstan is relatively flat with vast rangelands, which is already a good indicator for a high potential for the application of surface MAR methods, such as infiltration basins. Thus, the feasibility of MAR application in Kazakhstan is mostly defined by its soil and geology characteristics.

To the best of the authors' knowledge, this is the first published MAR potential map conducted in Central Asia. It was created as a means to raise awareness about the general applicability of MAR to the region and the possibility of integrating MAR systems into the local water management practises. To show the potential more explicitly, the exemplary region of Zhambyl was chosen, as it was prone to water shortage problems in the past.

By overlaying the MAR potential map with available water source (surface water bodies) and water users (irrigated agricultural lands), the applicability of the map for a more specific case study was shown. This process is flexible and water practitioners could use the map to overlay it with water sources and users specific to their region. By keeping this flexibility and not integrating potential water sources from the beginning, this map can be used in heterogeneous scenarios and keeps the option to integrate less common water sources, such as recycled water.

The scale and GIS information used for this map is large and relatively general. This is enough to give an overview for the whole country. When studying a smaller region, less coarse data should be used. However, this data was not available to the authors. Data availability is a restriction of this study, as we had to rely on openly available datasets. Therefore, this map is mostly showing the potential for surface MAR application, as mostly remote data sets of surface criteria, such as land use, slope, and soil type, were regarded. These remote data sets are generally more openly available than subsurface criteria.

It needs to be emphasized that this map should not be used to pinpoint to exact location where MAR sites can be built. Before selection a site for MAR application a more precise and detailed analysis is needed. The maps can be used in the early planning phase as a guidance tool to focus on certain sites for further investigation. This needs to be followed by subsequent in-situ measurements to characterize the hydrogeology and modelling studies to understand the impact of MAR application.

Rather than locating MAR sites, the purpose of the MAR potential map is to raise awareness about possibility of integrating MAR into the local water management plans. The potential is displayed through the graphic representation, which is a key feature when talking to stakeholders less familiar with the topic. The maps can also easily be adapted to regard future processes associated with climate scenarios, population growth, or land use changes. There already are MAR feasibility studies that show how these maps can be integrated into sustainable groundwater management plans and guidelines for groundwater enhancement (Magesh et al. 2012; Agarwal et al. 2013; Singh et al. 2013) as well as depicting MAR implementation as an investment option for farmers and policy makers (Owusu et al. 2017).

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Appendix

Appendix A1. Reclassified maps of hydrogeology (A), land use (B), slope (C), soil salinity (D) and soil type (E)