




Article

Identification of Potential Farm Pond Sites for Spring Surface Runoff Harvesting Using an Integrated Analytical Hierarchy Process in a GIS Environment in Northern Kazakhstan

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Abstract: People living in arid and semi-arid areas with highly variable rainfall often face droughts and floods that affect water availability. Surface runoff harvesting is a historical water delivery system utilized in times of water scarcity to fulfill the ever-increasing demand for water, address climate change, and prevent desertification. However, the study of snowmelt and flood water harvesting in steppe areas with cold and semi-arid climates are understudied in the international literature. This paper, combining remote sensing (RS) and a geographic information systems (GIS)-based analytical hierarchy process (AHP), provides a cost-efficient and reliable tool for assessing potential farm pond sites in the steppe region of Northern Kazakhstan. The research is based on six weighted thematic layers: hydrogeology (5%), slope (10%), drainage density (25.5%), land use/land cover (25.5%), soil (5%), and snow water equivalent (29%), which mainly influence the availability, runoff, infiltration, and accumulation of snowmelt and flood water, in order to identify potential farm pond sites in the Akkayin district (North Kazakhstan). As a result, 3.3% of the study area had a very high potential, 35.5% high, 56.5% medium, 4.6% low, and only 0.1% was recognized as the least preferred. The most suitable sites had medium drainage density, low slope, high snow water equivalent, and were located on flooded vegetation. The accuracy of our model was assessed using the existing farm pond sites from the Soviet era, which showed 82% coincidence. Furthermore, by collecting meltwater from 30% of the study area (135,000 ha), one-fourth of the cultivated land in the Akkayin district (i.e., 54,000 ha) could be transferred to deficit irrigation. This would reduce floods, stabilize farmers' income in dry years, and open up the possibility of cultivating other highly profitable crops. Overall, the study provides evidence of the great potential of the Akkayin district in snow meltwater harvesting in farm ponds as a response to agricultural drought and spring floods.

Keywords: snow meltwater harvesting; irrigation; climate resilience; multi-criteria decision analysis



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1. Introduction

Owing to intensifying climate change and shifting seasons, the northern grain-growing regions of the Republic of Kazakhstan suffer from regular droughts in the warm season and floods in the spring [1,2]. According to the agricultural drought-monitoring data of the CACILM-2 project of the FAO UN, in the period from 2001 to 2022, Akkaiyn district was not affected by droughts only for 8 years, which mainly occurred at the beginning of the millennium (2001–2007), and after 2016, the severity of drought increased on an annual basis (with the exception of 2018). Owing to the absence of major rivers in the

North Kazakhstan Region, most agricultural production focuses on rain-fed crops (i.e., crops without irrigation); drought is a major threat to crop failure [3]. There are three major crop types cultivated in the study area: cereals (wheat, barley, and oat), legumes (lentils, clover, alfalfa, and peas), and oilseeds (safflower, sunflower, rapeseed, and flax). The sowing campaign typically begins in mid-May and ends in October. According to a United Nations Development Programme report (Strategic Measures to Combat Desertification in the Republic of Kazakhstan Until 2025), drought is causing Kazakhstan to lose around 200 million euros annually [4]. At the same time, there is heavy precipitation in the solid form (snow) during the winter, which is accompanied by excess liquid precipitation in spring, resulting in devastating floods [5]. Hence, a record high water over the past half a century was recorded in 2017, which forced 4000 people to leave their homes and 15 flooded settlements [6]. In this regard, collecting snow melt and flood water in farm ponds could solve the abovementioned challenges caused by regular droughts and floods in the region [7,8]. This was practiced during Soviet times in the 1970s and 1980s, when thousands of farm ponds were created, most of which were for agricultural purposes. However, after the collapse of the Soviet Union in 1991, many farm ponds were abandoned, which led to an increase in the salinity of stagnant water. It must be noted that, when planning these ponds, the factors of climate change and increased spring floods were not taken into account. Thus, they were not aimed at solving flood problems in the region.

Spring surface runoff harvesting in farm ponds is “the management and collection of surface runoff to increase the availability of water for agriculture and domestic needs and to maintain the ecosystem” [9]. This is a historical water delivery system utilized in times of water scarcity to fulfill the ever-increasing demand for water, combat climate change and unpredictability, and prevent desertification. Spring surface runoff harvesting in farm ponds prevents erosion and flooding, and reduces water pollution at the same time [10]. This method has several advantages, such as regulating surface runoff during the spring flood season, providing water for irrigation, and mitigating water shortages during droughts using excess water. People living in arid and semi-arid areas with highly variable rainfall often face droughts or floods that affect water availability. The success of the spring surface runoff harvesting technique principally depends on the selection of a suitable location. Combining remote sensing (RS) and a geographic information systems (GIS)-based analytical hierarchy process (AHP) would be a cost-effective and reliable tool to assess potential farm pond sites. RS technology can gather, process, and manage vast amounts of data, allowing researchers to effectively investigate, analyze, and manage water resources. The GIS-driven AHP method, being the most preferred multi-criteria decision analysis (MCDA) tool in engineering, allows us to find the degree of superiority of one alternative over another according to specified criteria [11]. Despite the novel MCDA methods, such as CILOS, SAPEVO-M, MEREC, etc., proposed in the last decade, it is important to remember that no single method is perfect or suitable for application in all decision-making circumstances [12]. In this work, we have given preference to the traditional AHP method of the American School of Decision Support Systems [13]. This was justified by the fact that the AHP incorporates such qualities as an effortlessly reasonable system, the ability to disentangle a troublesome issue by dividing it into smaller steps, and the unnecessary of authentic information sets [13]. Furthermore, recent works on the identification of potential surface runoff (rainwater) harvesting using the AHP method proved the effectiveness of this approach, with an accuracy of 70 to 92% [10,14–17]. Table 1 provides a quick summary of recent studies on potential rainwater harvesting using MCDA methods. Nevertheless, the AHP model has a disadvantage in the limited number of pairwise comparisons. If the model contains a large number of criteria as well as alternatives, the decision-making process can take a long time, and over time, matrix inconsistencies can begin to increase due to loss of attention and lack of concentration on the subject. In our case, this problem was not material. Previously, several researchers utilized the above-mentioned approach with different parameters to assess groundwater potential [18–27], land suitability for solar farms [28–32], urban flood vulnerability [33–35], dam site selection along rivers [36–38],

and rainwater harvesting [10,14–17,39–41]. However, there is an immense gap in the study of spring melt and flood water harvesting in snowy, steppe areas with cold and semi-arid climates, as most similar works were carried out in tropical or desert areas, with no winter (Guatemala, Saudi Arabia, Taiwan, Iraq, India, Kenya, etc.) [10,14–17,39–41]. This is reflected in the input parameters and criteria chosen by the authors for the AHP model. For instance, Maina and Raude [41] used rainfall, slope, soil, land use/land cover, and distance from settlements and roads, Wu et al. [14] used the same parameters, but replaced rainfall with runoff, and Kadam et al. [40] included catchment size in this list. In general, about 75% of the list of parameters remained unchanged. It should also be noted that none of the previous works considered the snow cover factor, as this was not possible for their study areas.

Table 1. A quick summary of recent studies on identification of potential rainwater harvesting sites.

Reference	Year	Country	Applied method
Kadam et al. [40]	2012	India	Self-weighting
Chou et al. [39]	2014	Taiwan	Analytical Hierarchy Process
Maina and Raude [41]	2016	Kenya	Self-weighting
Wu et al. [14]	2018	Guatemala	Analytical Hierarchy Process
Alwan et al. [10]	2020	Iraq	Analytical Hierarchy Process
Sayl et al. [15]	2020	Iraq	Analytical Hierarchy Process
Balkhair and Ur Rahman [16]	2021	Saudi Arabia	Analytical Hierarchy Process
Chowdhury and Paul [17]	2021	India	Analytical Hierarchy Process

In contrast, in our research in the northern part of the Republic of Kazakhstan, snow cover is the most influential input parameter, as we assess the possibility of reserving snow meltwater in farm ponds for further agricultural use. This approach contributes to increasing water productivity in agriculture, which is very critical for arid and semi-arid areas. Water in farm ponds can be used for deficit irrigation; thus, farmers will not focus on achieving the maximum yield during dry periods, but will increase their economic benefits and income stability [42]. Nevertheless, experiments with deficit irrigation in Turkey that lasted for four years found that the wheat yield increased by 65% and the water productivity doubled compared with rainfed agriculture [43]. This fact has also been confirmed by studies in China [44,45], Syria [46], and Bangladesh [47].

Although there are many approaches to identifying potential rainwater harvesting sites worldwide using AHP methods, there is a great need for more advanced, new approaches adapted to cold, semi-arid, and steppe conditions. Thus, the main objective of this study is to evaluate the potential of the Akkayin district in snow meltwater harvesting in farm ponds for agricultural needs as a response to agricultural drought and spring floods. To achieve this, within the framework of this study, we set the goals to (1) develop an approach that can assess farm pond sites for snow meltwater harvesting in the cold, semi-arid steppe zone with high accuracy (>80%), (2) identify limiting factors, and (3) exclude field studies in the future that require a lot of time and resources. During the research, six parameters were considered to assess the potential zones of farm ponds: hydrogeology, slope, drainage density, land use/land cover, soil, and snow water equivalent, which mainly influence the availability, runoff, infiltration, and accumulation of snow melt and flood water in the Akkayin district, North Kazakhstan region. The use of these particular input parameters is based both on the existing literature and the opinion of three experts (two academic: Zhanat Toleubekova and Nurlan Balgabayev, and one industrial: Askar Abirov). It should also be noted that the snow water equivalent map was compiled based on the methodology developed by the authors earlier [48]. After assigning the weights to each factor using the AHP method, a map showing potential areas with low, medium, high, and very high snowmelt and floodwater storage potential for agriculture was prepared. Actual data from existing farm ponds in the study area were collected to assess the accuracy of the final result. The outcomes of the study can provide a basis for early warning of floods,

mitigation of agricultural drought, and, most importantly, socio-economic advancement in the region. Moreover, under the CC BY license, field snow survey data have been published for independent testing and comparative research by the international research community, and a freely accessible geoportal containing all research results has been created (see Data Accessibility Statement).

This work is organized as follows: (1) the materials and methods for selecting suitable sites for meltwater collection are thoroughly explained, (2) technical, economic, and environmental limiting factors are identified, (3) the results of the GIS-driven AHP implementation are discussed, and (4) conclusions and recommendations for future research are provided.

2. Materials and Methods

2.1. Study Area

The study area (see Figure 1) is one of the largest grain-sowing regions of Kazakhstan, the Akkayin district, which is located in the North Kazakhstan region. The area experiences a sharply continental climate characterized by a large amplitude of annual temperatures and dryness. Most of the region is located on the West Siberian lowland. The main feature of the relief is characterized by many closed basins with groups of lakes and single lakes. The distribution of precipitation over the years has been highly uneven. The average annual rainfall is typically between 225 and 335 mm. However, there have been years when the total annual precipitation rose above 600 mm or dropped to 204 mm. The coldest month is January, with an average mean temperature of -18.5 – -18.7 °C. The hottest month is July, when the average mean temperature is $+18.5$ – -18.7 °C. The average precipitation in winter varies between 22 and 42 mm. The snow cover in the area is unevenly distributed due to strong winds blowing away snow in open areas. During the summer, dry winds cause the soil to dry out quickly. The soils in the region are zonally distributed, so that ordinary loamy chernozems occur in the northern part, and to the south, they turn into southern chernozems with a lighter composition.

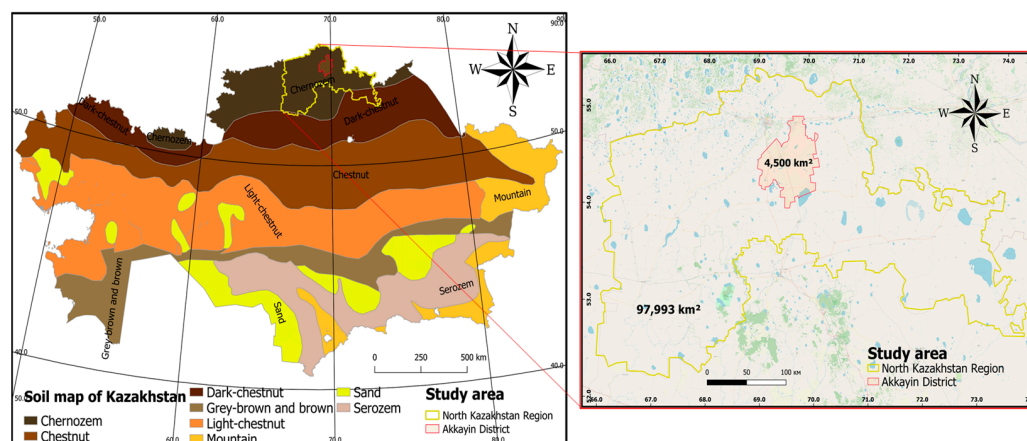


Figure 1. Study area and the soil map of the Republic of Kazakhstan.

2.2. Data Sources

2.2.1. In Situ Surveying

A field snow survey in key areas was carried out on two dates, in the middle (from 25 to 27 January 2023) and at the end (from 25 to 27 February 2023) of the winter season (Figure 2). In total, the depth of the snow cover was measured at 312 points, and the density at 65 points in the Akkayin district, North Kazakhstan region (see Table 2).

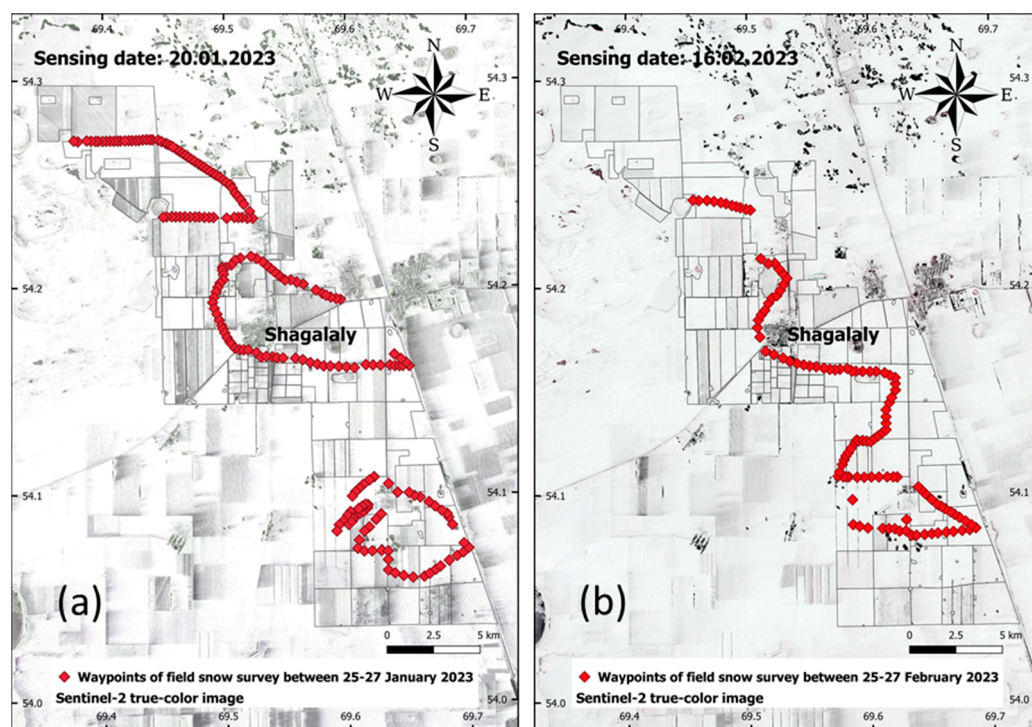


Figure 2. Waypoints of snow survey over the territory of Akkayin district, North Kazakhstan Region (a) between 25 and 27 January 2023 and (b) between 25 and 27 February 2023.

Table 2. Snow survey dates and number of measured points in the study area.

Snow Survey Dates and Number of Points	25–27 January 2023		25–27 February 2023	
	Depth	Density	Depth	Density
Territory of Akkayin District	197	39	115	26

A wooden snow gauge M-103 II (LLP “Seaguard-Group”, Almaty, Kazakhstan) with a division of 1 mm was used to measure the snow cover depth, and for snow density, a snow weight gauge VS-43M (LLP “Seaguard-Group”, Almaty, Kazakhstan) was utilized. The following equation was used to calculate the actual snow density:

$$\rho = \frac{m}{SD \times S} \quad (1)$$

where ρ is the density of snow in g/cm^3 , m is the mass of snow in g, SD is the snow depth in cm, and S is the area of the snow weight gauge VS-43M in cm^2 .

Owing to the difficulty of movement in the study area, most of which is occupied by snow-covered agricultural fields, an RM Vector 551i snowmobile (JSC “Russkaya mekhanika”, Ryabinsk, Russia) was used for fast movement (see Figure A1 of Appendix A). The accurate geopositioning of snow survey points was carried out using a Garmin Montana 610 system. All the gathered field snow survey data are available under the CC BY license in FigShare (see Data Availability Statement).

Moreover, a UAV survey was conducted between 16 and 21 August 2021 to build a detailed digital surface model (DSM) for further hydrological analysis. For this purpose, a fixed-wing UAV Supercam S350 (Unmanned Systems Group, Izhevsk, Russia) with a Sony A6000 (Sony Group Corporation, Minato, Japan) payload was used (see Figure A2 of Appendix A). The flight was carried out at a height of 1 km with a longitudinal overlap of 80% and a transverse overlap of 60%. Thus, 4368 images were received within six days, covering an area of around 45,000 ha. Ground control points (GCP) were not used due to

the vastness of the territory during the UAV survey. Nevertheless, the post-processing of the central points of all images was performed using data from the onboard dual-frequency GPS and Stonex S900 and S10 base stations.

2.2.2. Thematic Layers and Digital Satellite Image Datasets

Six thematic layers (hydrogeology, slope, drainage density, land use/land cover, soil, and snow water equivalent) essentially controlling melt and flood water availability were prepared based on the expert's opinion and the available literature. Hydrogeological maps on a scale of 1:200,000 compiled by the Kazakh Hydrological Department were digitized and used as input parameters. The slope and drainage density were mapped using a digital elevation model, while the land-use map was generated using high-resolution (10 m) satellite imagery (Sentinel-1 and Sentinel-2) and a knowledge-based classification method. The FAO-UNESCO Soil Map of the World database was used to prepare the soil map of the study area. Field snow survey data and Sentinel-2 MSI images with the nearest dates to the survey were utilized to prepare the most critical parameter, the snow water equivalent. The details of digital satellite image specification are provided in Table 3. Satellite images were downloaded from the Google Earth Engine (GEE) multi-petabyte catalog.

Table 3. Specifications of the Sentinel-2 multispectral instrument.

Sensor	Acquisition Date	Cloud Cover	Spectral Band with Wavelet (μm)
Sentinel-2	20 January 2023, 42UWE	1.13%	Coastal aerosol (0.443)
			Blue (0.490)
	20 January 2023, 42UWF	11.99%	Green (0.560)
			Red (0.665)
	16 February 2023, 42UWE	0%	Vegetation red edge (0.705)
			Vegetation red edge (0.740)
	16 February 2023, 42UWF	0%	Vegetation red edge (0.783)
			Near-infrared (0.842)
			Vegetation red edge (0.865)
			SWIR-Cirrus (1.375)
			SWIR-1 (1.610)
			SWIR-2 (2.190)

2.3. Methodology

The potential zones for snowmelt and flood water reservations were determined by overlaying all thematic layers in a weighted linear combination method using the spatial analysis tool in ArcGIS Pro 2.8 software. The relative weights of thematic layers and subgroups were determined using the analytical hierarchy process method. The conceptual model of the proposed framework is shown in Figure 3. The weights were set considering the opinion of a team of experts, which included one industrial and two academic experts. In addition, to identify unsuitable zones, a vector layer of agricultural land in the Akkayin district with a buffer zone of 1 km was used to identify productive zones for reserving melt and flood waters for agriculture. We considered collecting and reserving meltwater at a distance of more than 1 km from agricultural land inefficient.

2.3.1. Identification of Unsuitable Zones to Reserve Melt and Flood Water

At this stage of research, a feasibility study was carried out regarding the potential to reserve melt and flood water in the Akkayin district. During the designation of potential areas for reserving melt and flood water for agricultural use, it is necessary to consider some technical, economic, and environmental factors. From a technical point of view, it is not justifiable to reserve meltwater in remote places and extend miles of pipes to agricultural fields. From an economic point of view, agricultural enterprises would need to purchase a large number of necessary goods, such as pipes, and maintain them, which requires enormous financial and labor resources. From an environmental point of view, we excluded

areas with a high content of harmful metals (metalloids) in water, such as manganese and arsenic, which is unacceptable for agricultural use. For this purpose, six meltwater samples were taken at key points to conduct chemical water analysis in May 2022. Detailed results of the chemical analysis of meltwater are provided in the test report (see Figure A3 of Appendix A). For example, the analysis recorded an excess of the maximum allowable norm of arsenic by three times (the norm is 0.05 mg/dm^3 , and the measured value was 0.16 mg/dm^3). In addition, to create a buffer zone of 1 km, the boundaries of agricultural land in the study area were digitized in the .shp format (Figure 4).

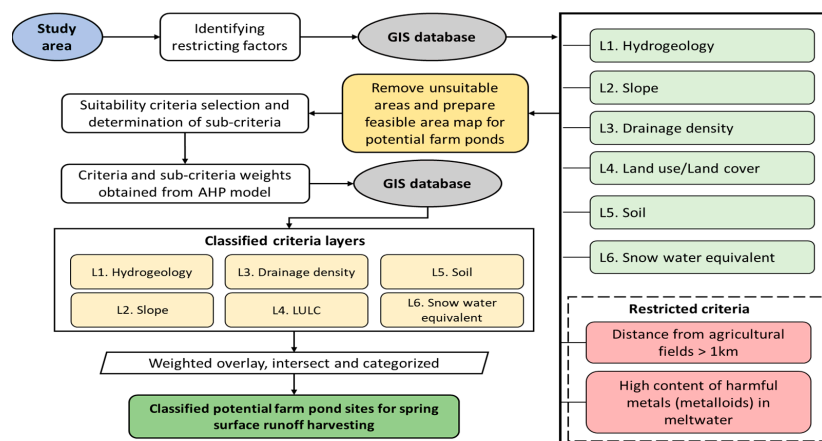


Figure 3. The conceptual framework of the research.

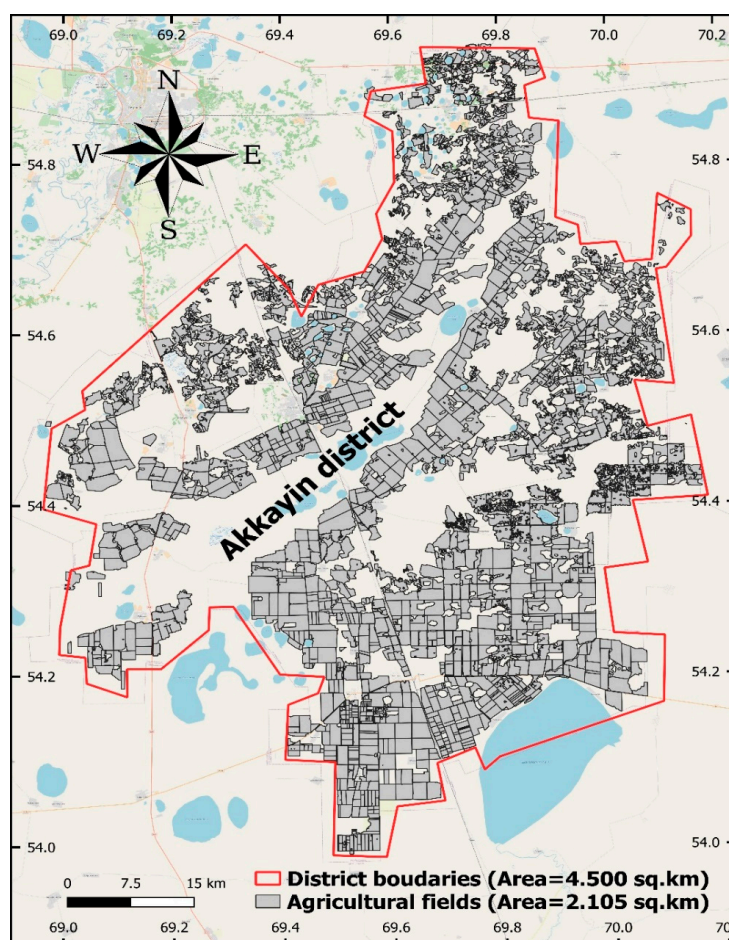


Figure 4. Digitized boundaries of agricultural fields in the study area.

2.3.2. Preparation of Thematic Layers

On the basis of the existing literature and expert opinions, eight thematic layers were created. To avoid unnecessary complications, experts removed two thematic layers, and the remaining six layers were weighted based on the AHP method (see Figure A4 of Appendix A). Further, explanations are provided regarding specific thematic layers.

Hydrogeology

The hydrogeological map displays the conditions of the occurrence, distribution patterns, and formation of groundwater [49,50]. As these maps are based on the results of hydrogeological surveys, considering geological and tectonic maps, parameters such as the lithological composition of aquifers and mineralization were important in this study. A hydrogeological map of the study area was digitized using ArcGIS Pro 2.8 software.

Slope

The slope gradient, which depicts the steepness of the Earth's surface, is a crucial relief component. According to Melese and Belay [25,51], a moderate slope has the maximum potential for infiltration, whereas a steeper slope produces more runoff. The slope is one of the more important parameters when choosing zones for reserving melt and flood waters, the average value of which in the Akkayin district is about 2%. In our case, sites with a slope of more than 5% had lower potential as surface runoff increased. The slope gradient map was created from the digital elevation model using the spatial analyst toolbox in ArcGIS Pro 2.8 software, which utilized the following formula:

$$S = \sqrt{\left(\frac{dZ}{dx}\right)^2 + \left(\frac{dZ}{dy}\right)^2} \quad (2)$$

where S is a slope in 3D, dZ/dx is the horizontal difference in height divided by the distance between pixels, and dZ/dy is the vertical difference in height divided by the distance between pixels.

Drainage Density

Another factor that affects the evaluation of locations for snowmelt and floodwater storage in farm ponds is drainage density. According to several researchers [19,52,53], locations with high drainage density inevitably have high runoff, which, in turn, suggests poor infiltration rates and reserve potential. In this paper, we consider that the most preferable areas for farm ponds should be downstream, but below the highest drainage density value. To create a drainage density map of the study area, we performed multiple geoprocessing operations, such as stream ordering to identify and classify streams from the digital elevation model based on the number of tributaries and creating a grid index. Finally, the drainage density was calculated by the following equation using the Line Density tool in ArcGIS Pro 2.8 software:

$$DD = \frac{\sum_1^n L}{A} \quad (3)$$

where DD is the drainage density, L is the stream length, and A is the basin area.

Land Use/Land Cover

Land use and land cover significantly influence surface runoff, the infiltration rate, water consumption, and snow accumulation [54]. Accordingly, strongly snow-blown bare ground, built-up areas, and water bodies were classified as the least-preferable areas for snowmelt and flood water storage, while flooded vegetation, grasslands, and shrubs were the top-three areas with a favorable environment for constructing farm ponds. The land use/land cover map of the study area was created using high-resolution Sentinel-1 and

Sentinel-2 imagery, and a knowledge-based classification method was obtained from the ESRI LULC 2021.

Soil

According to Anbazhgan et al. and Etikala et al. [55,56], soil cover influenced surface water runoff and infiltration rate, which, in turn, affected the availability of melt and flood water for the reservation. The soil's physical characteristics, including grain size and pore space, could also strongly impact groundwater recharge [57,58]. In comparison with fine-grained soils, coarse-grained soils are known to have a high infiltration rate and cause a larger loss of surface runoff in reserving snow meltwater in farm ponds [59]. However, due to global climate change, snow cover is melting faster than usual when the ground is still frozen to a depth of 1 to 1.5 m. According to the permafrost-measuring device (merzlometr) installed in the regional center of the Akkayin district, the depth of soil freezing varied from 45 cm to 197 cm between October 2022 and April 2023. Thus, in the early spring, regardless of the soil type, meltwater does not infiltrate the soil and, in turn, causes destructive floods. In this study, a soil map of the study area was obtained from the FAO/UNESCO Soil Map of the World portal.

Snow Water Equivalent

The snow water equivalent was the most important parameter in this study, as it integrally characterized the depth and density of snow cover that was theoretically planned to be reserved in the farm ponds. Additionally, this parameter fully described the snow reserves in a particular area and could clarify the water regime of rivers and lakes [48]. A high-resolution (10 m) snow water equivalent map of the study area was prepared using the authors' previously developed and validated methodology for assessing the depth of snow cover and snow water equivalent using remote sensing data and GIS technologies. The main approaches and methods for calculating the snow water equivalent are shown in Figure 5. All calculations were carried out on the Google Earth Engine multi-petabyte cloud platform, and the source codes are available at the following link [60].

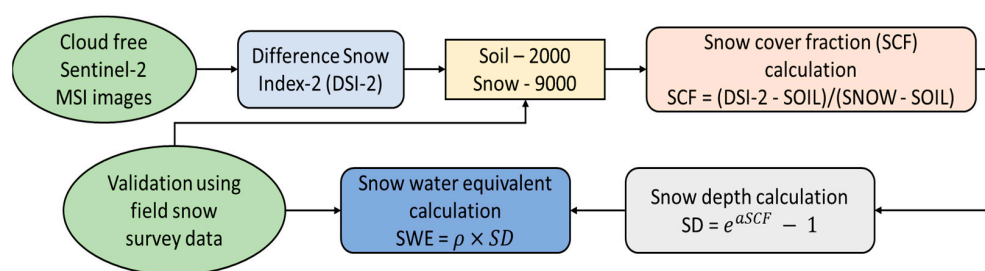


Figure 5. Flow chart of the methodology for calculating the snow water equivalent.

2.3.3. Assigning Relative Weights

Each thematic layer has a distinct effect on the runoff, infiltration, and accumulation of melt and flood waters on the Earth's surface [23,61]. The relative weight of the input parameters was determined by using the AHP method and was based on the degree of influence of layers on the occurrence and dynamics of surface waters [62]. As the hierarchy-based structure of the decision issue was essential to the AHP method, determining the primary criteria, sub-criteria, alternatives, and hierarchy structure was a significant component of the decision process. The hierarchical structure of this process is illustrated in Figure 6.

This model has been frequently employed as a decision-making tool in issues requiring intricate parameters and domains with constrained data, both in terms of variety and reliability [63,64]. In the current research, expert judgment and an eigenvector were applied to assign weight and order to the input layers, while the principal eigenvalue was used to rank the factors [65–67]. To define the relative significance of indicators based on Saaty scale values [62], a hydrogeologist with industrial experience was recruited from the Kazakh

Research Institute of Water Management, and two academic experts were involved from the local university (Table 4).

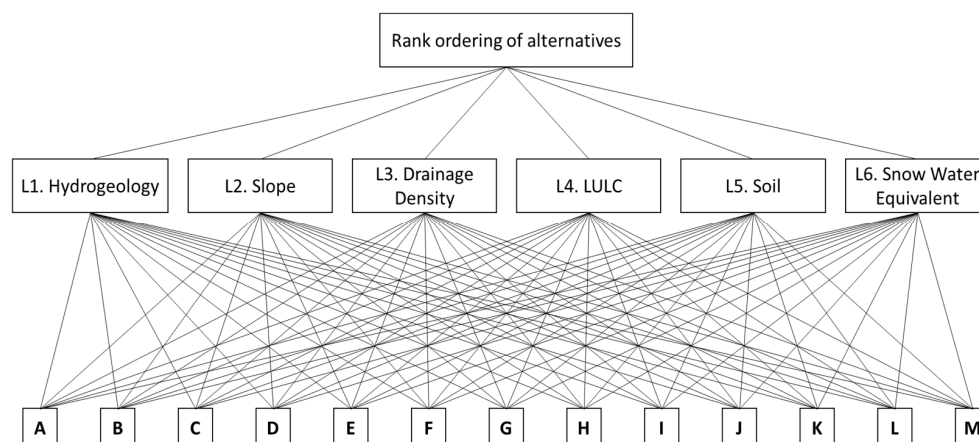


Figure 6. Hierarchy structure of the identification of potential farm pond sites.

Table 4. Analytical hierarchy process significance scale by Saati.

Scale	1	2	3	4	5	6	7	8	9
Importance	Equal	Weak	Moderate	Moderate plus	Strong	Strong plus	Very strong	Highly strong	Extreme

By dividing the column values by the column grand total, the eigenvector—representing each indicator’s relative weight [68]—was created, as illustrated in Table 5. The consistency of the matrix was measured by the sum of the eigenvalues (principal eigenvalue λ_{max}), and a pairwise comparison matrix (6×6) was created using the input factors. Each entry describes how the relative row has an impact on the column factor. By contrasting the λ_{max} values of the pairwise comparison matrix with different thematic layers present, the validity of the matrix was evaluated. It is important to note that the total number of parameters was less than λ_{max} . When indications are solved in pairs, a certain degree of consistency may develop. Therefore, verifying the given weight’s correctness in a pairwise comparison is crucial.

Table 5. Relative weights of input layers compiled with expert judgment.

Layers	SWE	Hydrogeology	Slope	Drainage Density	LULC	Soil
SWE	1	5	5	1	1	5
Hydrogeology	1/5	1	1/3	1/3	1/5	1
Slope	1/5	3	1	1/3	1/3	3
Drainage Density	1	5	3	1	1	5
LULC	1	5	3	1	1	5
Soil	1/5	1	1/3	1/5	1/5	1
Sum (col)	3.6	20.0	12.7	3.9	3.7	20.0

Given that the discrepancy of the matrix grew with the number of comparisons, the AHP technique incorporated a consistency index to track variance. A consistency ratio lower than 10% was required to determine the weight; otherwise, the relative weights of each indicator should have been changed to mitigate the disparity [69]. The consistency

index, as illustrated in the formula, was the ratio of the difference between λ_{\max} and the total amount of input layers used.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (4)$$

$$CR = \frac{CI}{RI} \quad (5)$$

where CI is the consistency index, λ_{\max} is the principal eigenvalue, n is the number of layers, CR is the consistency ratio, and RI is a random index.

Table 6 shows that the principal eigenvalue for this research was 6.15, which was higher than the total number of input layers, and that the consistency ratio of 2% was also within the tolerance limit (10%), showing that both the given weighting and consistency in pairs were appropriate.

Table 6. Evaluation of pairwise matrix consistency.

Layers	Column Sum (1)	Principal Eigenvector (2)	Rank (1 × 2)
SWE	3.60	0.290	1.045
Hydrogeology	20.00	0.047	0.943
Slope	12.67	0.100	1.268
Drainage Density	3.87	0.258	0.996
LULC	3.73	0.258	0.962
Soil	20.00	0.047	0.943
λ_{\max}			6.158

Moreover, each input layer was reclassified into a common ratio scale and combined to produce a map of potential farm pond sites (PFPSs) to store melt and flood water. All reclassified rasterized maps were overlaid using the Weighted Overlay analysis tool. Finally, the weighted values of each raster layer were multiplied by the cell score of each input raster. In addition, potential farm pond sites were classified based on the potential farm pond site index value. The PFPS index was a dimensionless value calculated from the weights of each thematic layer and its characteristics. The PFPS index was calculated using the following formula:

$$PFPS_i = \sum_{i=1}^n w_i x_i$$

where PFPS_i is the potential farm pond sites index, n is the number of layers, W is the normalized weighting of the layer, and x_i is a relative score of the *i*th layer at the *t*th pixel.

2.3.4. Validation of Farm Pond Sites

Regarding the scientific relevance of this study, model validation is essential to assess the reliability of the results [70]. In this work, the identified potential areas of farm ponds for snowmelt and flood water storage were tested using existing farm ponds, or rather, their digitized vector layers (see Figure A5 of Appendix A). In the literature, other researchers also used ground data to cross-check the developed model for identifying potential zones [71–73]. The observed data on existing farm ponds were digitized, geo-positioned, and overlaid on a delineated map of potential farm pond areas for melt and flood water storage in a GIS environment. Thus, the share of existing farm ponds located in zones with low, medium, high, and very high potentials was calculated.

3. Results

In this research, six parameters (hydrogeology, slope, drainage density, land use/land cover, soil, and snow water equivalent) that mainly influence the runoff, infiltration, and accumulation of surface melt and flood water were carefully considered in the study area

to assess the potential zones for the location of farm ponds. After assigning weights to each factor using the AHP method, a map of potential areas with low, medium, high, and very high snowmelt and floodwater storage potential for agriculture was compiled.

3.1. Hydrogeology

As the hydrogeological map combined both hydrological and geological characteristics of the area, parameters such as the infiltration rate, runoff, mineralization, and lithological composition of the aquifer were considered essential. The study area was classified into three classes: Pliocene–Quaternary aquifer, Quaternary lacustrine–alluvial aquifer, and Neogene aquifer, and their areas accounted for 323,700 ha (70.4%), 88,600 ha (19.3%), and 47,500 ha (10.3%), respectively (Figure 7). In this study, the Neogene aquifer had low potential for farm pond construction sites, because most of its territory was already occupied by salty lakes unsuitable for agriculture. The quaternary lacustrine–alluvial aquifer was assigned medium potential, because it has a low infiltration rate and higher runoff. However, this class tends to be very well sorted with highly laminar clays and sometimes carbonates that do not allow common crops of the region to be cultivated. The Pliocene–Quaternary aquifer, with lower mineralization but a high infiltration rate occupying almost three-quarters of the Akkayin district, was the most suitable for reserving melt and flood water for agriculture.

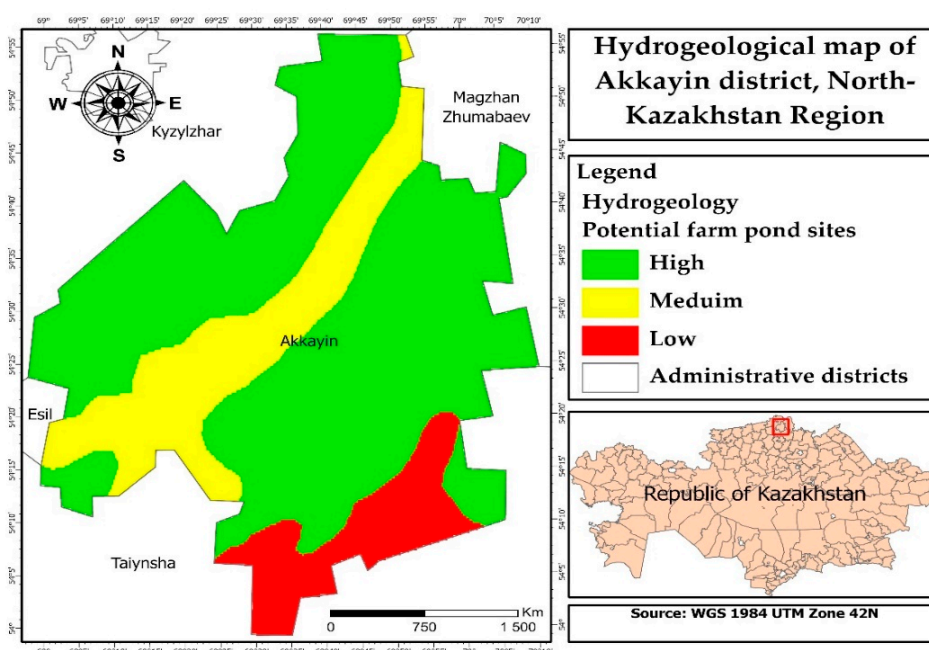


Figure 7. Reclassified hydrogeological map of Akkayin district.

3.2. Slope

Slope is an important parameter when it comes to selecting zones for reserving melt and flood waters, the average value of which is about 2% in the Akkayin district. Generally, the steeper the slope, the greater the runoff, and conversely, a moderate slope provides more potential for surface water infiltration. The slope map of the study area was classified into five classes, namely very high (0–1%), high (1–2%), medium (2–3%), low (3–4%), and very low (>4%) potential areas (Figure 8). The results showed that more than 80% of the Akkayin district is suitable for farm pond construction in terms of surface relief, as 42% of the territory had a score of very high potential and 40.5% had high potential. Nevertheless, 64,153 ha (14%) was found to have medium, 12,074 ha (2.6%) low, and 4287 ha (0.9%) very low potential to reserve spring surface runoff.

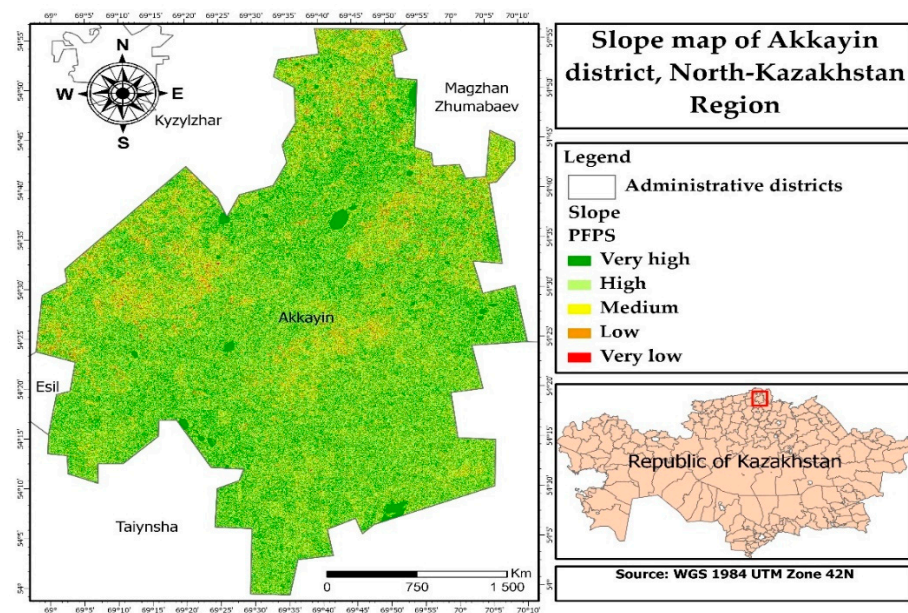


Figure 8. Reclassified slope map of Akkayin district.

3.3. Drainage Density

Drainage density was the second most important parameter after the snow water equivalent in this study. Commonly, locations with high drainage density inevitably have high runoff, which, in turn, suggests poor infiltration rates and reserve potential. The drainage density map of the Akkayin district had five similar classes to the slope map. During classification, we granted more preference to drainage density values higher than zero but below the maximum. Thus, the areas with very high drainage density had very low potential (1.3%), high drainage density areas had low potential (8.5%), and very low drainage density areas had medium potential (29%) for snow meltwater reservation. Very high potential was found in areas with low drainage density (34.5%), and areas with an average drainage density had high potential (26.7%) (Figure 9). To sum up, more than 60% of the study area was found to be suitable for farm ponds in terms of drainage density.

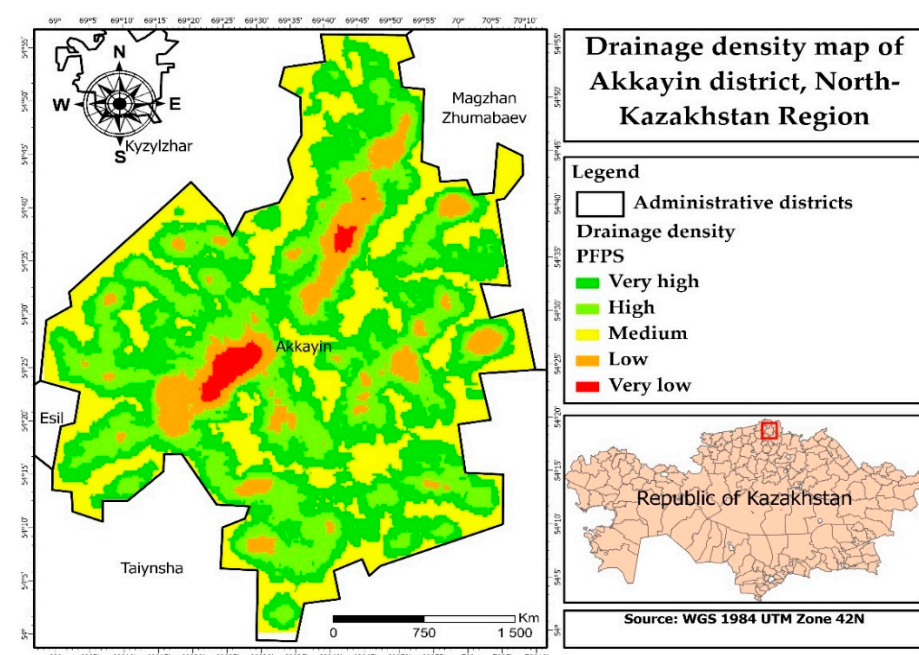


Figure 9. Reclassified drainage density map of Akkayin district.

3.4. Land Use/Land Cover

The third most important parameter, the land use/land cover map, originally had eight classes, but was reclassified into five, similar to the previous maps' classes (Figure 10). As built-up areas are unsuitable for agriculture and bare ground surfaces are useless for snow meltwater reservation, they were amalgamated into one class with very low potential for farm pond site construction (0.9%). Low potential was also afforded to water bodies (2%), because most of them had high mineralization and were located relatively far from agricultural fields. Trees and crops were also grouped together and classified as areas with medium potential (59.1%), while shrubs were considered more suitable for farm pond sites and ranked as surfaces with high potential (24.1%). According to the opinion of experts, grass and flooded vegetation surfaces were the most appropriate fields for snow meltwater reservation, occupying only 13.9% of the study area.

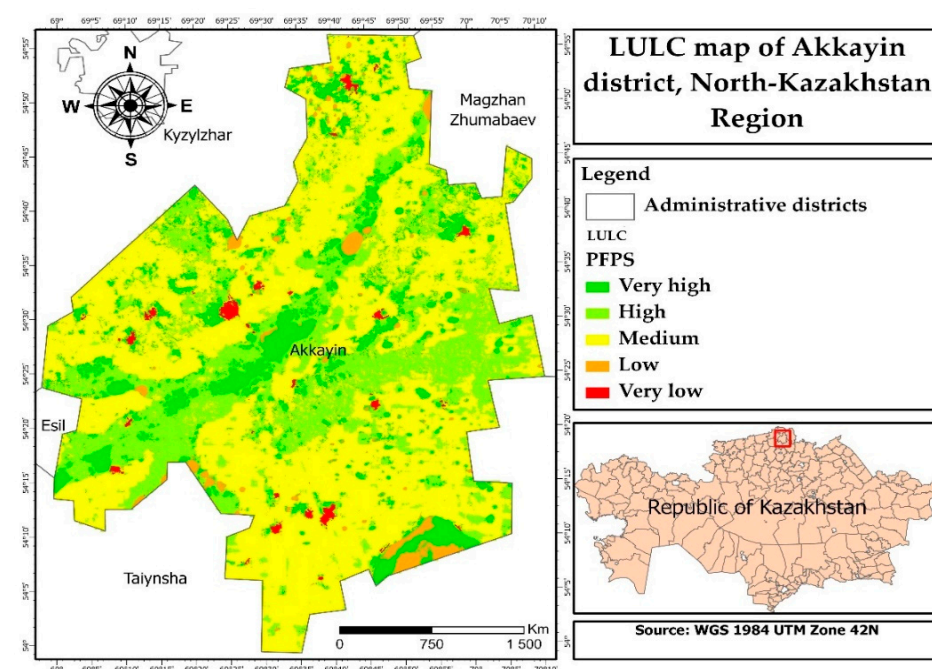


Figure 10. Reclassified land use/land cover map of Akkayin district.

3.5. Soil

The soil map of the study area consisted of four classes: ordinary chernozems, ordinary carbonate chernozems, ordinary solonetz chernozems, and solonetz (Figure 11). Based on its physicochemical characteristics, solonetz with excessive alkalinity, which is harmful to many crops, was classified as an area with very low (4%) potential for farm ponds. Further, depending on the degree of salinity, ordinary solonetz chernozem had medium potential (27.2%), ordinary carbonate chernozem high (7.2%), and ordinary chernozem had very high (61.6%) potential for reserving melt and spring water for agriculture. Considering that the infiltration and water-holding capacity of the watershed depended on the structure, mechanical composition, and soil type, these properties were not considered when ranking the classes, as the type (chernozem) and subtype (ordinary) of soil were the same throughout the Akkaiyn region.

3.6. Snow Water Equivalent

A high-resolution snow water equivalent map of the study area was prepared using the earlier methodology of the authors [48]. After all, in the framework of this study, it was planned to assess the snow cover and the possibility of its reservation in the spring for agricultural needs. Thus, the snow water equivalent map was the most crucial parameter in the hierarchy structure. The final map was reclassified into five classes, and the ranking was

based on the rule that the more snow, the better (Figure 12). According to the map, zones with very low potential occupied 5.9% of the study area ($SWE \leq 10 \text{ kg/m}^2$), zones with low potential covered 6.9% ($SWE \leq 20 \text{ kg/m}^2$), and the area of the medium-potential zone accounted for 8.6% ($SWE \leq 30 \text{ kg/m}^2$). Such a small share of unsuitable territories indicates that the region receives an enormous amount of precipitation during the winter, affording good potential for snow meltwater reservation in spring. Accordingly, territories with a snow water equivalent between 30 and 40 kg/m^2 and more than 50 kg/m^2 were classified as zones with high (19.8%) and very high (58.8%) potential for farm pond sites, respectively.

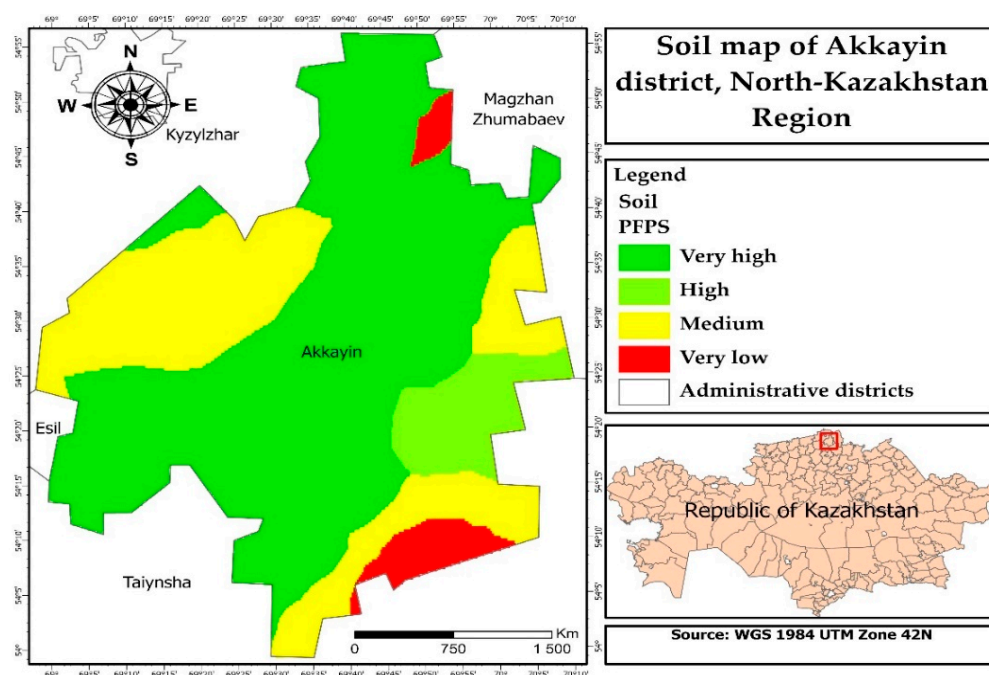


Figure 11. Reclassified soil map of Akkayin district.

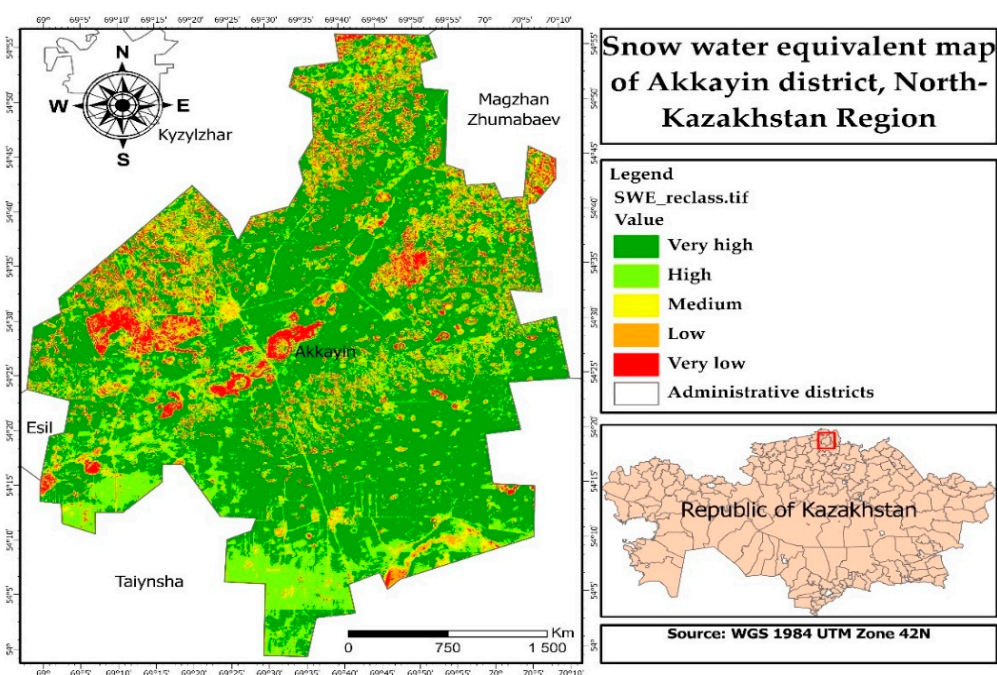


Figure 12. Reclassified snow water equivalent map of Akkayin district.

3.7. Overall Assessment of Potential Farm Pond Sites

Weights were assigned to each input parameter using the experts' opinions and the AHP methodology described in Section 2.3.3. As a result, the snow water equivalent map had the most significant weight (29%), drainage density and land use/land cover maps had the same weight, which was equal to 25.5%, slope was assigned a less significant weight (10%), and hydrogeology and soil cover maps equally had the smallest share in the weighting, accounting only for 5% (Figure 13). According to our understanding, this is the most appropriate weight distribution for the northern steppe regions of the Republic of Kazakhstan and regions with similar soil and climatic conditions.

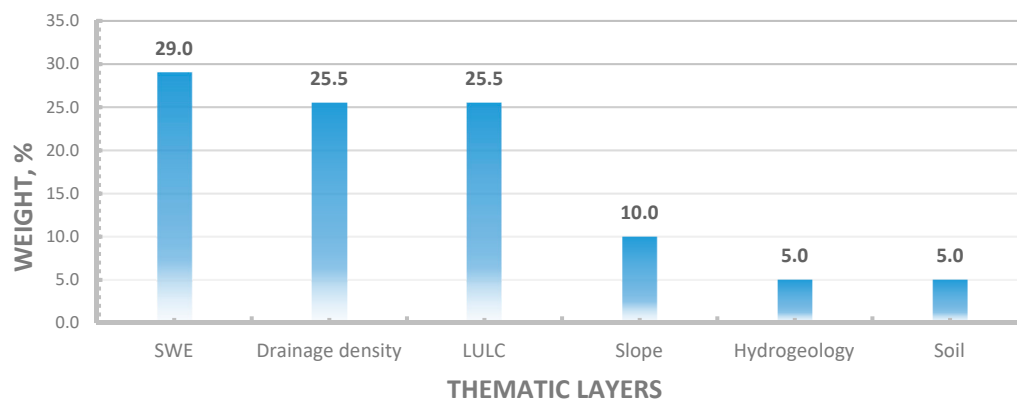


Figure 13. The relative weights of the potential farm pond site indicators.

Furthermore, using the Weighted Overlay tool in ArcGIS Pro 2.8 software, weights and ranks were assigned to each input parameter and their classes in the GIS environment. Thus, after reclassifying and layering maps of unsuitable zones (1 km buffer zone from agricultural land and the results of the chemical analysis of water), a final map of potential farm pond sites for spring surface runoff harvesting was obtained (Figure 14). As in the previous cases, the map with potential zones was classified into five categories: very high (3.3%), high (35.5%), medium (56.5%), low (4.6%), and very low (0.1%) potential. When unsuitable areas were skipped, the 450,000-hectare surface of the study area decreased to 370,000 ha. In the remaining territory, the area of the most reasonable sites for reservation of snow meltwater was 12,224 ha, while the territory with high potential occupied 131,502 ha. Shrubs and flooded vegetation with medium drainage density and high snow water equivalent occupied a major part of the most suitable territories for farm ponds. The largest part of the Akkayin district, accounting for almost 210,000 ha, fell into zones with medium potential. According to our results, the greater share of agricultural fields had medium potential for snowmelt reservation in the study area. On the other hand, water bodies, built-up areas, and territories with high slope and drainage density were classified as zones with low (17,039 ha) and very low (370 ha) potential. The results illustrate that they formed a relatively smaller proportion of the study area, but, in fact, many unsuitable zones (e.g., saline and clayey soils, high drainage density, and low snow water equivalent) coincided with the clipped areas with a buffer zone of 1 km from agricultural fields. Overall, almost 145,000 ha of productive land was found to be suitable for harvesting spring surface runoff in small farm ponds in the Akkayin district.

3.8. Validation of Potential Farm Pond Sites Map

To validate the final results for potential farm pond sites for spring surface runoff harvesting, existing farm ponds from the Soviet era in the Akkayin district were digitized (see Figure A5 of Appendix A). These farm ponds were created in the 1970s and 1980s with bulldozer technology; some of them are funnels that were deliberately blown up with explosives. Given that the topographic and geodetic works were carried out during the planning stages of these massive farm ponds, we believe that the most suitable places

from a geographical point of view were chosen. Thus, we overlaid a vector file with 121 existing farm ponds on the final map showing potential zones. We found that not a single Soviet-type farm pond was located in a low-potential zone (0%), while 18% of them were constructed on a territory with medium potential (see Figure A6 of Appendix A). This is because some farm ponds were also supplied with groundwater using drilled wells, thus being located close to existing settlements and also serving livestock. However, 79% of the Soviet farm ponds (95) were located in a high-potential zone, and 3% in a zone with very high potential. On average, the qualitative assessment of potential melt and flood water reservation areas matched more than 80% of the ground data of existing farm ponds. This means that our data highly correlate with the areas of existing sites using the analytical hierarchy process in the GIS environment.

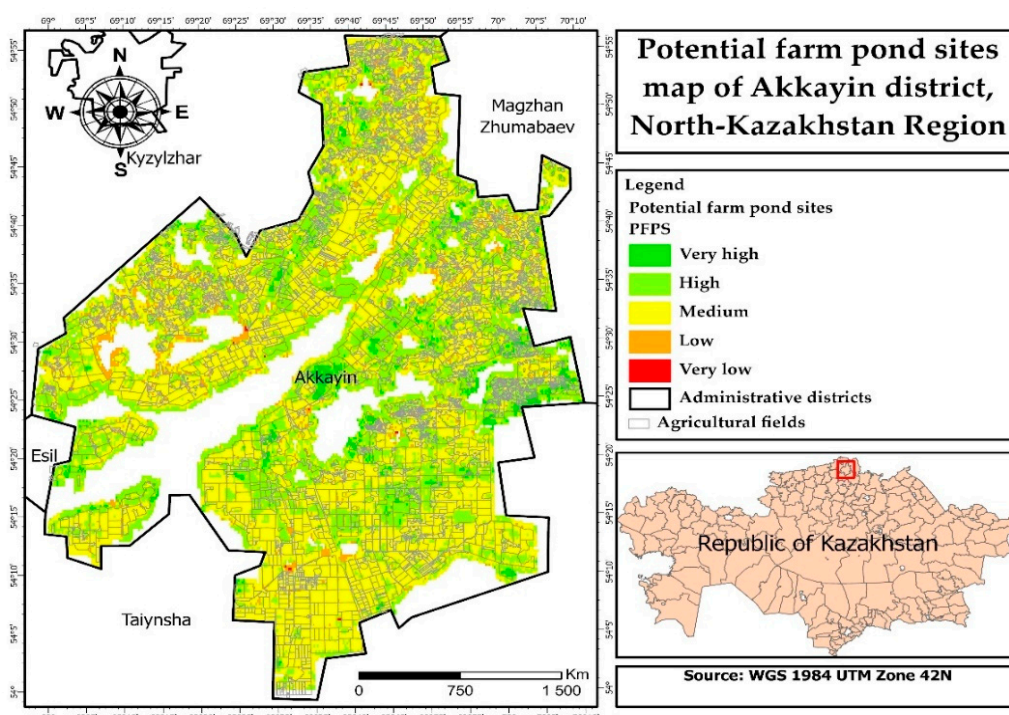


Figure 14. Overall potential farm pond sites for melt and flood water reservation map of Akkayin district, North Kazakhstan region, overlaid on agricultural fields.

4. Discussion

Our results indicate that the GIS-driven AHP method performed well in identifying potential farm pond sites for snow meltwater harvesting in the study area. The results also show that the Akkayin district has a great potential to utilize excess surface runoff in agriculture, which creates opportunities for sustainable agriculture in the future amidst climate change. Previous studies showed that, by using the AHP methodology, it is possible to determine potential groundwater zones [22,25,52] and flood-vulnerable areas [33,34] with an accuracy of 70 to 92%, while the current work achieved a precision of 82%, which was in line with the average accuracy range of earlier works. Compared with similar studies related to the identification of potential rainwater harvesting sites [10,14–17,40,41], this study used a snow parameter that was not previously taken into account. We found that snow was a major cause of spring floods and was also a possible solution to drought in the region. It all depends on the planning and management of natural resources. According to long-term data from field snow surveys in the Akkayin district, the territory is annually covered with 20 cm of snow, and the average snow density reaches 300 kg/m³. This means that one square meter of land contains about 60 L of snow water, or 600 m³ per hectare. Suppose we assume that water losses through evaporation and infiltration are 15%. In this case, the meltwater collected from the territory of 5 hectares will be enough for 1 ha of

wheat under fully fledged irrigation or 2 ha under deficit irrigation [74]. Considering this proportion, it is easy to calculate that, theoretically, by collecting meltwater from 30% of the study area (135,000 ha), one-fourth of the cultivated land in the Akkayin district, which accounts for 54,000 ha, can be transferred to deficit irrigation. This would not only reduce floods and stabilize farmers' income in dry years, but would also open up the possibility of cultivating other highly profitable crops. Accordingly, local municipalities would receive more taxes, and they would spend less money to restore infrastructure after devastating floods. This would lead to more sustainable development in the region, increase economic growth and social responsibility, and maintain ecological balance.

Nevertheless, during this research, we also found that using the AHP method in a GIS environment for the delimitation of potential zones had several limitations: (1) the results obtained were partially subjective, as they partly depended on the opinion of experts, (2) although the primary approach remained unchanged, the weighting of input parameters and sub-criteria were strongly tied to a particular geographic area and could not be scaled, and (3) adding/removing alternatives to/from the existing model led to a change in the preferential order of other alternatives without alternating the values of pairwise comparisons concerning individual criteria. Considering the advantages and limitations of the identification of potential farm pond sites for spring surface runoff harvesting using an integrated AHP in a GIS environment, we expect that our approach will be helpful for sustainable water management, improving the socio-economic conditions of the population, and the development of irrigated agriculture in the Akkayin district, North Kazakhstan.

Overall, the potential of the Akkayin district in snow meltwater harvesting in farm ponds for agricultural needs as a response to agricultural drought and spring floods was found to be great. This is because the region receives a huge amount of precipitation in the winter and spring every year, and the snow melts very quickly due to climate change. Even though the territory of the Akkayin district is covered with highly water-holding capacity chernozem, the snow meltwater does not infiltrate the soil, as it remains frozen to a depth of 1–1.5 m until April. This creates destructive floods, high surface runoff, soil erosion, and the possibility of excess water retention in farm ponds.

5. Conclusions

In this study, the identification of potential farm pond sites for surface runoff harvesting in the Akkayin district, North Kazakhstan region, was carried out using a GIS-driven AHP method and six input parameters: hydrogeology, slope, drainage density, land use/land cover, soil, and snow water equivalent, which mainly influence the availability, runoff, infiltration, and accumulation of snowmelt and flood water. As a result, 3.3% of the study area was recognized as a very-high-potential zone, 35.5% high, 56.5% medium, 4.6% low, and 0.1% as a very-low-potential zone. The most suitable territories were found to have medium drainage density, low slope, high snow water equivalent, and be located on flooded vegetation and shrubs. Moreover, the majority of cultivated agricultural land was classified to have medium potential, despite the significant amount of snow water stored and moderate slope. On the other hand, the less preferred zones formed a relatively smaller proportion of the study area, but the larger part of them coincided with the clipped areas with a buffer zone of 1 km from agricultural fields. As a result, using ground-based surveys, remote sensing, and AHP in a GIS environment, potential zones for farm ponds were obtained with an accuracy of 82%. The model accuracy was assessed by using the locations of existing farm ponds. Furthermore, limiting factors, such as the high content of harmful metals in meltwater and the optimal distance of farm ponds from agricultural fields, were also identified. The use of the model allows us to avoid field studies that require a lot of time and resources in further research. We think that our approach can be suitable for regions with similar soil and climatic conditions to Northern Kazakhstan to address drought and spring flood challenges through sustainable management and increasing water productivity. Further work is planned to evaluate the possible socio-economic effects

of introducing sustainable water management by snowmelt and flood water harvesting in farm ponds and increasing water productivity in irrigation.

Author Contributions: Z.T. (Zhanassyl Teleubay) analyzed the data and drafted the manuscript; F.Y., I.T., Z.T. (Zhanat Toleubekova) and N.B. completed the manuscript and made major revisions; A.A. searched for references; Z.K. revised and proofread the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The field snow survey data used in the current work are openly available under the CC BY license in FigShare at <https://doi.org/10.6084/m9.figshare.c.6651380.v1> (accessed on 13 June 2023). As part of the project, a geoportal was built: <https://maps.gistech.kz/niwater/> (accessed on 13 June 2023).

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AHP	Analytical hierarchy process
CC BY	Creative Commons Attribution License
CI	Consistency index
CILOS	Criterion impact loss
CR	Consistency ratio
DD	Drainage density
DEM	Digital elevation model
DSM	Digital surface model
FAO UN	Food and Agriculture Organization of the United Nations
GCP	Ground control points
GEE	Google earth engine
GIS	Geographic information system
GPS	Global positioning system
LULC	Land use and land cover
MCDA	Multi-criteria decision analysis
MEREC	Method based on the removal effects of criteria
MSI	Multispectral instrument
PFPS	Potential farm pond sites
RI	Random index
RS	Remote sensing
SAPEVO-M	Simple aggregation of preferences expressed by ordinal vectors group decision making
SD	Snow depth
SWE	Snow water equivalent
UAV	Unmanned aerial vehicle
UNESCO	United Nations Educational, Scientific and Cultural Organization

Appendix A



Figure A1. The process of measuring the snow height and density.



Figure A2. The process of conducting a field UAV survey in the study area.

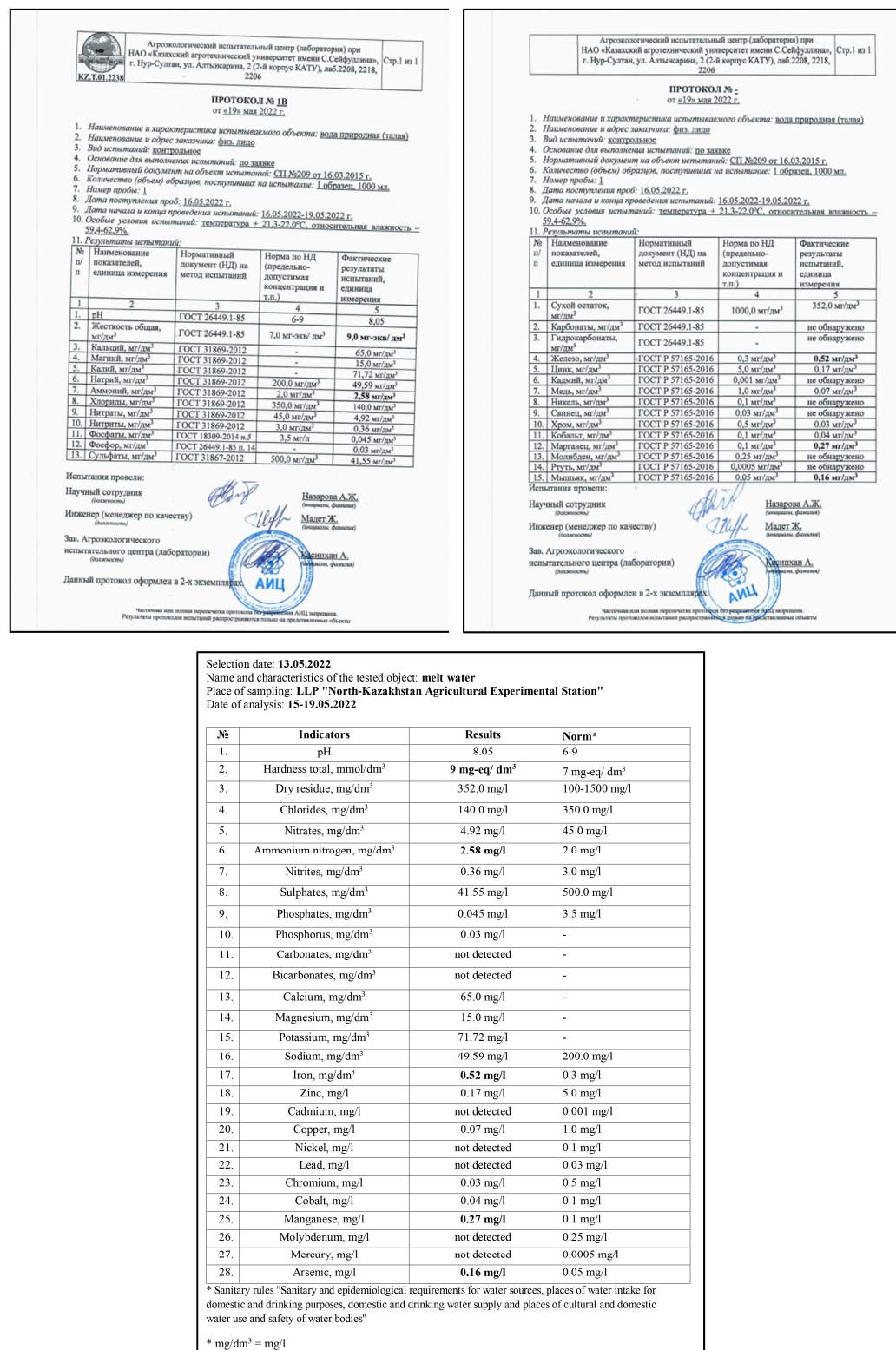


Figure A3. Results (protocol) of the chemical analysis of meltwater at critical points of Akkayin district, North Kazakhstan region, and its English translation.

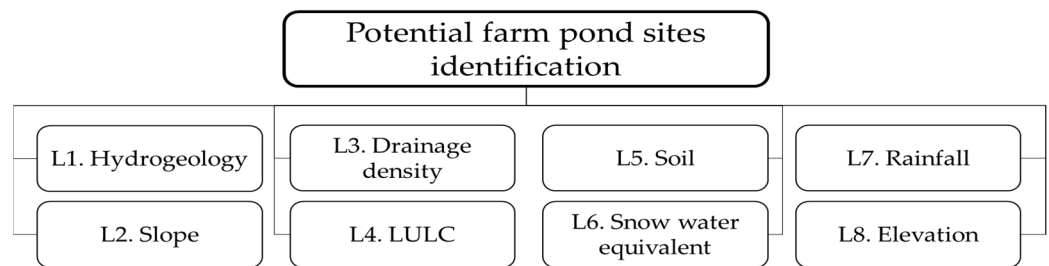


Figure A4. Input thematic layers for potential farm pond site identification.

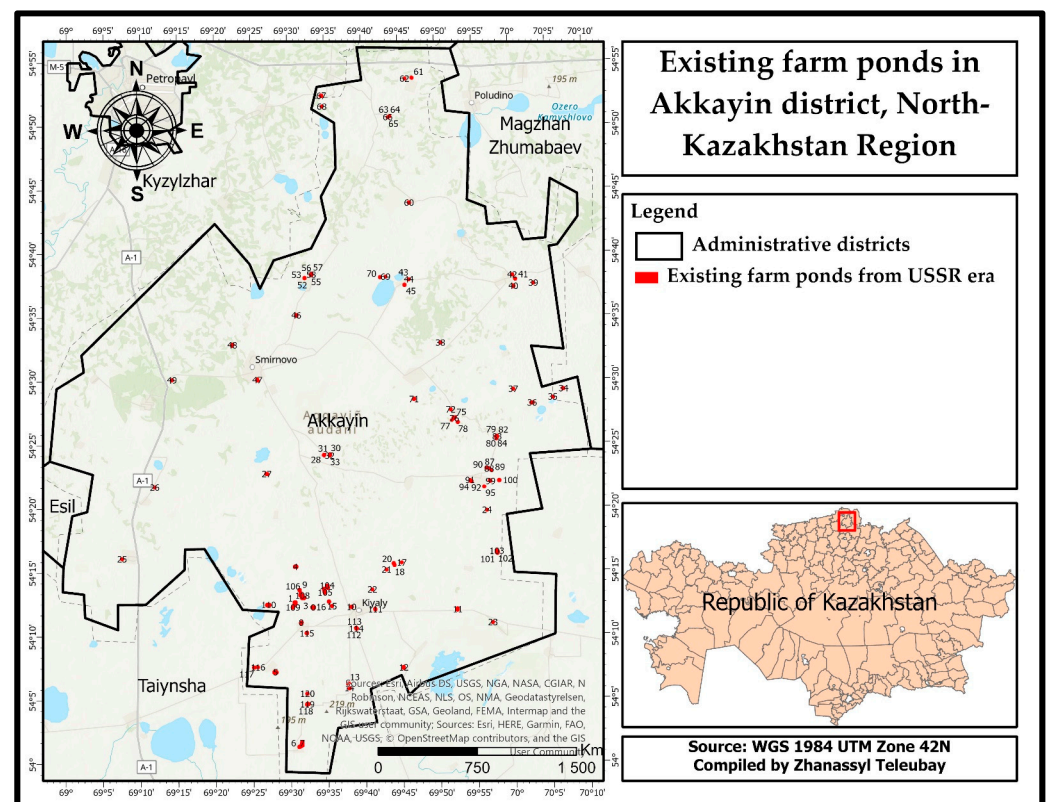


Figure A5. Existing farm ponds from the USSR era in Akkayin district, North Kazakhstan region.

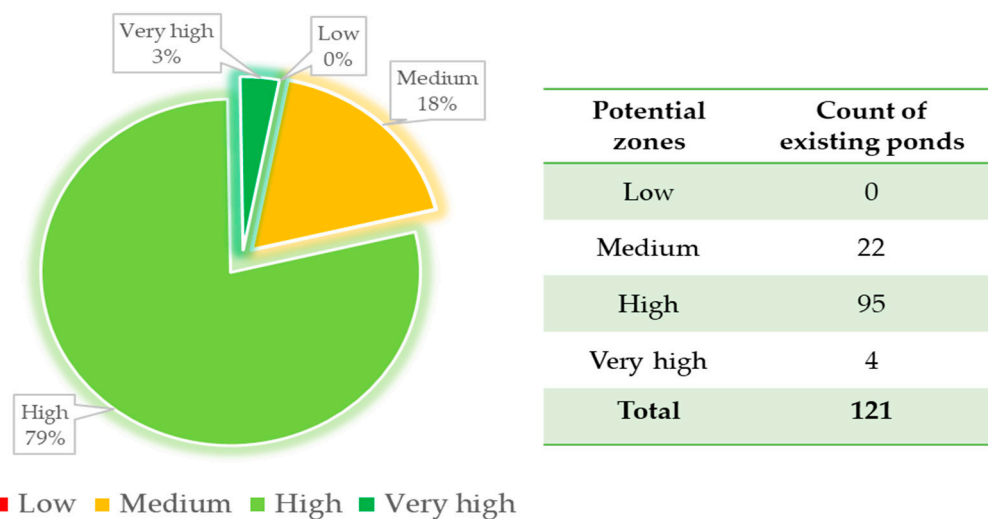


Figure A6. Share of existing farm ponds in the developed map of potential zones.

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