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TOWARD CLIMATE-RESILIENT AGRICULTURE IN NORTHERN KAZAKHSTAN: INTEGRATING SNOWMELT-BASED DROUGHT MITIGATION, CROP MODELING, AND YIELD IMPACT ASSESSMENT

Summary of PhD Dissertation

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1. Problem Statement

Northern Kazakhstan's agricultural productivity is increasingly threatened by climate change, marked by severe droughts and destructive spring floods. These extremes pose serious risks to wheat production, which is vital for Kazakhstan's economy and food security in Central Asia. Despite the region's importance, adaptation has lagged behind due to limited water infrastructure. Traditional irrigation systems are scarce, making agriculture highly vulnerable to changing precipitation and rising temperatures.

Winters bring heavy snowfall, followed by rapid warming that causes accelerated snowmelt. This valuable water resource is largely lost, as the meltwater flows over frozen or saturated soils, triggering flash floods that damage infrastructure and farmlands. As the season advances, dry conditions prevail, worsening soil moisture deficits and increasing crop stress. The mismatch between water availability in spring and water demand during summer is deteriorating due to climate change. Projections suggest earlier and faster snowmelt, longer dry spells, and more frequent extreme events in the future.

Moreover, the problem is compounded by socio-economic and institutional factors. Many rural farming communities lack the financial resources or technical capacity to invest in advanced irrigation or water storage solutions. Water management policies remain fragmented, and there is limited integration between climate projections, agricultural planning, and local water governance. As a result, adaptation measures are often reactive rather than preventive, leaving the sector vulnerable to further climate shocks.

The absence of data-driven planning tools also hampers informed decision-making. Although global climate models and remote sensing technologies have advanced considerably, their application to localized agricultural water management in cold semi-arid regions like Northern Kazakhstan remains limited. Without integrating scientific data with spatial decision-making tools, opportunities for cost-effective and sustainable solutions, such as snowmelt harvesting, will continue to be overlooked. Addressing these gaps requires not only technical innovations but also a paradigm shift in how snowmelt is perceived: from a flood hazard to a strategic resource for climate-resilient agriculture.

2. Research Objectives and Questions

This research aims to tackle the pressing challenges posed by climate change to agriculture in Northern Kazakhstan. The region's reliance on rainfed wheat farming means that any shifts in precipitation patterns, temperature, or snowmelt timing can have significant consequences for farmers and food security more broadly. In recent years, farmers have struggled with frequent droughts during the growing season, while also having to deal with damaging floods from fast-melting snow in the spring. These weather extremes are becoming more common, and without proper water management systems in place, agricultural productivity remains highly exposed. The urgency of the situation is underscored by climate projections that forecast even more erratic seasonal cycles in the future, with earlier snowmelt, hotter and longer summers, and increased rainfall variability. These changes are expected to intensify stress on already fragile agricultural systems. Current water infrastructure is not equipped to capture and redistribute water when it is most needed. Therefore, building local capacity to manage water more efficiently and predict crop responses under different climate scenarios is critical.

To address these issues, this dissertation explores how snowmelt, a resource that is currently underutilized, can be captured and stored to provide much-needed water during dry periods. The study combines innovative technologies like satellite-based snow monitoring with established tools such as crop simulation models and geospatial decision-making techniques. By bringing together satellite imagery, crop modeling tools, and spatial analysis techniques, the research provides a new approach to managing water and land more efficiently. This integrated approach not only provides technical insights but also supports the development of localized strategies that are practical, sustainable, and adaptable to changing environmental conditions.

Based on the above, the main questions of my doctoral research are the following:

1. How will projected climate change scenarios (under different RCPs) affect wheat yields in Northern Kazakhstan, and which agroecological zones are most vulnerable?

2. To what extent can remote sensing methods accurately estimate snow depth and snow water equivalent (SWE) in the region using remote sensing and field data?

3. Which areas in Northern Kazakhstan offer the highest suitability for constructing small-scale farm ponds to harvest snowmelt, based on environmental, hydrological, and land-use criteria?

4. What is the potential contribution of snowmelt harvesting to reducing agricultural drought risk and improving yield stability by the mid-century?

3. Data and Methods

This dissertation builds on a mix of research methods, including fieldwork, remote sensing, crop modeling, and geospatial analysis, to assess and develop sustainable water management strategies for agriculture in Northern Kazakhstan. A wide variety of data sources and analytical techniques were used to meet the study's interdisciplinary goals, which include simulating climate impacts on wheat yields, estimating snow resources, and identifying suitable sites for snowmelt harvesting infrastructure. The approach integrates quantitative models, field observations, satellite imagery, and expert knowledge within a GIS environment.

To simulate how wheat yields respond to future climate conditions, the DSSAT model was used. The widely cultivated spring wheat variety "Shortandy 95" served as the target crop, chosen for its regional adaptability and drought tolerance. A genotype file was developed to capture the physiological and agronomic characteristics of this cultivar. Future climate projections were sourced from two advanced Earth System Models: MPI-ESM1.2 and GFDL ESM4.1, both of which provided daily climate data at a suitable resolution for Northern Kazakhstan. Simulations were run under three RCP scenarios, RCP 2.6, RCP 4.5, and RCP 8.5, to capture a range of possible climate futures from moderate to extreme. The projection period focused on 2036-2065, allowing for mid-century assessments of yield vulnerability.

To parameterize the soil conditions in the DSSAT model, detailed soil profile data were obtained from the SoilGrids global database. Soil attributes included bulk density, soil texture, organic carbon content, nitrogen levels, and pH across six depth intervals (5 cm to 200 cm). Agronomic management practices were based on recommendations from the North Kazakhstan Agricultural Experimental Station. Uniform planting dates (May 13) were applied across the study area for consistency, while other parameters like sowing depth (5-8 cm), seeding rate (250-400 seeds/m^2), and row spacing varied depending on soil and agro-climatic zones.

To validate remote sensing estimates of snow resources, field surveys were conducted between January 30 and February 9, 2022, across three key agricultural enterprises in Northern Kazakhstan. In total, 410 snow depth and 285 snow density measurements were taken. Snow depth was measured manually, while snow density was determined using the VS-43M weight snow gauge, which calculates density from snow mass, depth, and the area of the gauge. These observations provided ground truth data for calibrating satellite-based snow indices and estimating SWE. High-resolution Sentinel-2 MSI multispectral imagery was used to monitor snow cover conditions. Satellite scenes were selected to match the field survey dates as closely as possible, with some areas having images from up to four days before or after the ground measurements. A mosaic of images with different cloud cover levels was compiled to ensure full spatial coverage of the study region. All images were accessed through the GEE cloud platform.

To estimate snow depth and SWE from satellite data, several snow-sensitive spectral indices were applied: Normalized Difference Snow Index (NDSI), Difference Snow Index (DSI), and Ratio Snow Index (RSI). Among these, the DSI-2 index demonstrated the strongest statistical correlation with observed snow depth and density. Quadratic regression models were developed between index values and field measurements, yielding high predictive accuracy ($R^2 > 0.88$). These models enabled the mapping of SWE across the entire study area, forming the basis for identifying zones with the greatest snowmelt potential.

To locate optimal areas for farm ponds that could store spring snowmelt and reduce summer drought stress, six thematic layers were created: hydrogeology, slope, drainage density, land use/land cover, soil type, and SWE accumulation zones. Each of these layers contributed unique information about site suitability, such as infiltration potential, runoff behavior, terrain stability, and snow resource availability. The AHP was used to assign relative weights to each of the thematic layers based on expert judgment. These layers were then integrated using a weighted overlay analysis in a GIS environment to create a composite suitability map. This approach provided a practical framework for spatial decision-making, guiding future investment in small-scale water storage infrastructure. To ensure practicality, a 1 km buffer was applied to exclude sites too far from cropland areas. Additionally, chemical water quality testing of snowmelt samples was conducted, and areas exceeding safe contaminant levels (e.g., arsenic) were excluded from the final recommendations. The final suitability maps were validated against existing pond infrastructure to assess their accuracy and reliability. This end-to-end process, from data collection to model development and spatial validation, ensures that the results are grounded in local realities and provide actionable insights for climate adaptation in Northern Kazakhstan.

4. Results of Doctoral Research

4.1. Projected climate change impacts on wheat yields

The first part of the doctoral research examined the vulnerability of Northern Kazakhstan's wheat production to climate change using the DSSAT crop simulation model within the CRAFT v3.4 framework. Simulations were conducted for the mid-21st century (2036-2065) under three IPCC Representative Concentration Pathways, RCP 2.6, RCP 4.5, and RCP 8.5, using daily climate data.

Results indicate a consistent decline in average wheat yields across the region, with projected reductions of 9% under RCP 2.6, 17% under RCP 4.5, and 26% under RCP 8.5 relative to the baseline period. The southern and central zones, characterized by lighter soils with lower water-holding capacity, showed the steepest declines, in some cases exceeding 300 kg/ha yield loss.

Spatially explicit model outputs (Figure 1a-c) revealed a clear north-south gradient of vulnerability, with relatively higher resilience in the northern forest-steppe due to cooler summer temperatures and deeper chernozem soils. Under high-emission scenarios (Figure 1b-c), the optimal wheat-growing zone is projected to shift to the central region, reducing the suitability of current breadbasket areas. These findings highlight a dual challenge for the region: projected warming not only accelerates phenological development, shortening the grain-filling period, but also increases evapotranspiration demand, thereby intensifying soil moisture deficits during critical reproductive stages.

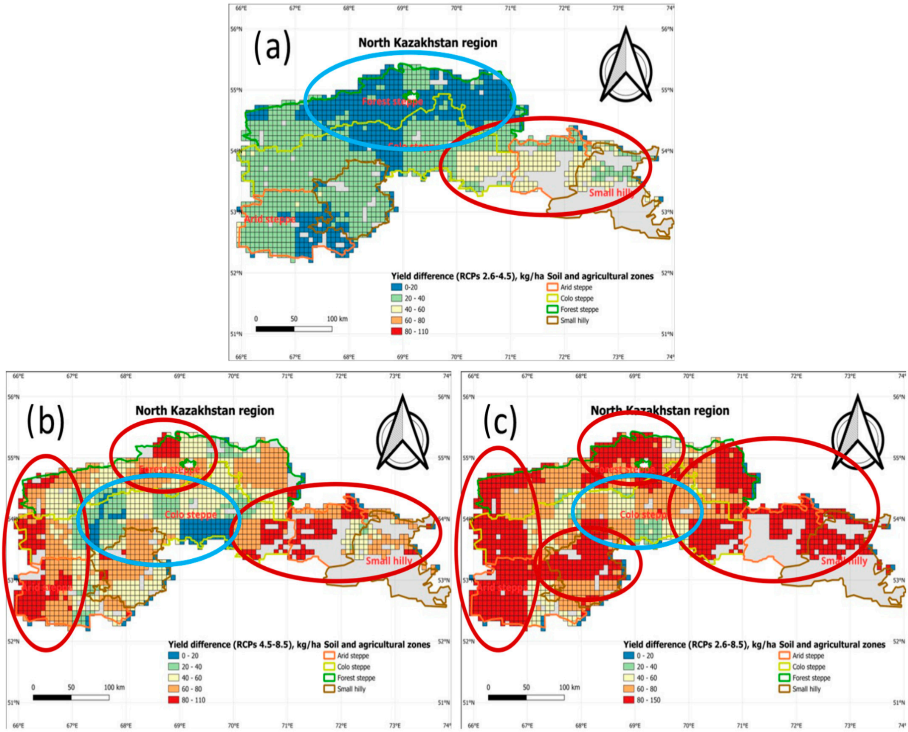

Figure 1. The spatial distribution of yield changes under each RCP scenario, illustrating zones of high and low vulnerability.

4.2. Remote sensing–based snow monitoring methodology

Recognizing the importance of snowmelt as a potential water source, the second stage of the research developed and validated a remote sensing methodology to map snow depth and SWE at high resolution. Field surveys conducted between 30 January and 9 February 2022 collected 410 snow depth and 285 snow density measurements across three representative agricultural enterprises in different soil zones.

The snow depth mapping produced eight high-resolution outputs corresponding to the tested snow indices: NDSI-1, NDSI-2, NDSII-1, NDSII-2, RSI-1, RSI-2, DSI-1, and DSI-2. Each index was applied to Sentinel-2 MSI imagery and converted to depth values using quadratic regression equations derived from field-measured snow depth data. These maps revealed substantial spatial variability in snow accumulation within the "North Kazakhstan Agricultural Experimental Station" and its surrounding agricultural landscapes. Across all index outputs, the general pattern was consistent: the highest snow depths, exceeding 30 cm, occurred in wind-protected zones such as forest shelterbelts, along field boundaries, and in local depressions where snow drift and deposition were more pronounced. Moderate depths of 10-30 cm were widespread across level cultivated fields, while low depths of 0-10 cm were concentrated in exposed upland areas and open fields lacking windbreaks, where strong prevailing winds redistributed snow cover.

Although the overall spatial trends were similar, the level of spatial detail and boundary sharpness varied considerably between indices. The DSI-2 index consistently produced the clearest delineation of snow-non-snow boundaries, capturing fine-scale heterogeneity and avoiding overestimation of snow cover in bright bare soil or settlement areas. RSI-2 and NDSI-2 also performed relatively well, although their definition in transitional zones was slightly lower. By contrast, the NDSII-1 and NDSII-2 indices tended to underestimate snow depth in sheltered areas and produced noisier outputs in heterogeneous land-cover patches, which reduced their precision for local-scale applications.

The quantitative accuracy assessment presented in Table 1 corroborates these visual interpretations. Correlation coefficients (R) and root mean square error (RMSE) values were calculated for each index against independent field measurements across three validation sites: LLP "North Kazakhstan Agricultural Experimental Station," LLP A.I. Barayev "Research and Production Center for Grain Farming," and LLP "Naidorovskoe." DSI-2 achieved the highest accuracy across all sites, with R values of 0.78, 0.69, and 0.80, and the lowest RMSE values of 5.62 cm, 3.46 cm, and 2.86 cm, respectively. RSI-2 ranked second overall, achieving R values up to 0.55 with RMSE as low as 3.27 cm, performing better than NDSI variants in capturing variation in open agricultural fields. NDSI-2 showed moderate accuracy with R values up to 0.53, while NDSII indices generally exhibited weaker relationships, with R values near zero or negative and higher RMSE values, confirming their limited utility in the study area's mixed land-cover and high reflectance conditions.

Table 1. Modeled snow depth error assessments

Study Area	Error	NDSII-2	NDSII-1	NDSI-2	NDSI-1	RSI-2	RSI-1	DSI-2	DSI-1
LLP "North Kazakhstan Agricultural Experimental Station"	R	0.45	0.20	**0.53**	0.24	0.55	0.25	**0.78**	0.51
	RMSE	6.85	7.45	**6.44**	7.02	**6.16**	6.66	**5.62**	7.29
LLP A.I. Barayev "Research and Production Center for Grain Farming"	R	−0.07	−0.01	−0.06	0.00	−0.06	0.00	**0.69**	0.50
	RMSE	4.75	4.69	4.84	**4.67**	4.85	4.86	**3.46**	4.10
LLP "Naidorovskoe"	R	0.26	0.18	**0.44**	0.41	0.44	0.40	**0.80**	0.51
	RMSE	3.47	3.53	3.40	3.50	**3.27**	3.35	**2.86**	3.17

The SWE maps derived from these snow depth outputs further illustrated the implications for water resource potential. SWE distribution closely mirrored snow depth patterns, with the highest values concentrated in forest belts, field depressions, and sheltered topographic features, which function as natural snow traps. Open, wind-exposed croplands exhibited markedly lower SWE, highlighting their vulnerability to sublimation and wind erosion losses. These patterns have direct operational relevance, as they identify priority catchment areas for snowmelt harvesting and demonstrate that relatively small, strategically located catchments can yield substantial volumes of meltwater. The superior performance of the DSI-2-derived SWE maps makes them particularly well-suited for integration into water management planning, where the precise identification of high-yield snow zones can significantly improve the cost-effectiveness and success of pond placement.

The results show that while all indices are capable of depicting general snow distribution trends, DSI-2 consistently provides the highest statistical accuracy and clearest spatial representation. The high-resolution SWE maps generated through this approach enable cost-effective and repeatable seasonal monitoring, supporting the integration of snowmelt into regional water management strategies.

4.3. Identification of optimal farm pond sites for snowmelt harvesting

The third stage of this research focused on the practical challenge of determining where farm ponds should be located to maximize the capture and storage of snowmelt. A GIS-based AHP model was developed using six thematic layers: hydrogeology (5%), slope (10%), drainage density (25.5%), land use/land cover (25.5%), soil type (5%), and snow water equivalent (SWE) (29%). The assigned weights, determined through expert consultation and literature review, reflected the relative influence of each factor on pond suitability, with SWE receiving the highest weight due to its direct role in seasonal water availability.

The resulting suitability map classified the Akkayin district into five categories: very high, high, medium, low, and least suitable. It shows that the very high suitability zones (3.3% of the area) are clustered primarily in depressions and sheltered valleys where snow accumulation is greatest. High suitability zones (35.5%) extend across much of the central and eastern portions of the district, while medium suitability (56.5%) dominates areas with moderate slopes, mixed land cover, and lower SWE values. Only a small fraction falls into the low or least suitable categories, typically in elevated or poorly drained zones.

Model validation against Soviet-era pond locations revealed an 87% spatial match, confirming the robustness of the suitability assessment. In the very high suitability areas, strategically placing ponds close to existing farm infrastructure could reduce conveyance losses, improve water delivery efficiency, and support timely irrigation during peak crop water demand.

Water balance calculations, based on snow survey-derived SWE values, indicated that 5 hectares of catchment could generate enough meltwater to fully irrigate 1 hectare of wheat under full irrigation, or 2 hectares under deficit irrigation. When scaled up, capturing meltwater from 30% of the district’s land could supply supplemental irrigation to approximately one-quarter of the cropland, providing a substantial buffer against summer drought stress.

5. Summary

- The doctoral research demonstrated that Northern Kazakhstan's wheat production is highly vulnerable to projected mid-century climate change, with yield declines of approximately 9%, 17%, and 26% under RCP 2.6, RCP 4.5, and RCP 8.5, respectively. The largest losses are expected in the southern and western zones with lighter soils and lower water-holding capacity. These findings underscore the dual threat of accelerated phenological development and increased evapotranspiration demand, intensifying drought risk during reproductive stages.
- Spatial modeling revealed a north-south gradient of vulnerability, with the cooler forest-steppe zone showing higher resilience (RCP 2.6) and a projected shift of optimal wheat-growing zones toward central areas under high-emission scenarios (RCPs 4.5 and 8.5).
- A remote sensing methodology was developed and validated for high-resolution mapping of snow depth and SWE using Sentinel-2 imagery and field survey data. Eight snow indices were evaluated, with DSI-2 achieving the highest accuracy across all validation sites (R up to 0.80, RMSE as low as 2.86 cm), followed by RSI-2 and NDSI-2.
- The snow depth and SWE maps revealed substantial spatial heterogeneity in snow accumulation, with forest shelterbelts, depressions, and wind-protected areas consistently exhibiting the highest SWE values. These zones represent priority catchments for snowmelt harvesting and illustrate the potential of targeted seasonal water capture in cold semi-arid agricultural landscapes.
- The SWE-based mapping demonstrated that strategically identified high-yield snow zones can be monitored cost-effectively on a seasonal basis, providing a robust tool for integration into regional water management planning.
- A GIS-based AHP model was applied to identify optimal farm pond locations for snowmelt harvesting in the Akkayin district, using six weighted thematic layers (SWE, drainage density, land use/land

cover, slope, soil type, and hydrogeology). SWE was assigned the highest weight (29%) due to its critical role in water availability.

- The resulting suitability map classified 3.3% of the district as very highly suitable, 35.5% as highly suitable, and 56.5% as moderately suitable for pond construction. Validation against Soviet-era pond locations showed an 87% spatial match, confirming the model's reliability.
- Water balance calculations indicated that 5 hectares of high-SWE catchment can fully irrigate 1 hectare of wheat (or 2 hectares under deficit irrigation). Scaling to 30% of the district's land area could supply supplemental irrigation to roughly one-quarter of its cropland, significantly improving drought resilience.
- By integrating climate change impact assessment, advanced remote sensing, and spatial decision-support modeling, the research reconceptualizes snowmelt from a flood hazard to a strategic seasonal water resource. This approach offers a replicable framework for climate-resilient water management in cold semi-arid agricultural regions.

6. List of publications used in the dissertations

Teleubay, Z., Yermekov, F., Rustembayev, A., Topayev, S., Zhabayev, A., Tokbergenov, I., Garkushina, V., Igilmanov, A., Shelia, V., & Hoogenboom, G. (2024). Comparison of Climate Change Effects on Wheat Production under Different Representative Concentration Pathway Scenarios in North Kazakhstan. Sustainability, 16(1), Article 1. https://doi.org/10.3390/su16010293

Teleubay, Z., Yermekov, F., Tokbergenov, I., Toleubekova, Z., Igilmanov, A., Yermekova, Z., & Assylkhanova, A. (2022). Comparison of Snow Indices in Assessing Snow Cover Depth in Northern Kazakhstan. Sustainability, 14(15), Article 15. https://doi.org/10.3390/su14159643

Teleubay, Z., Yermekov, F., Tokbergenov, I., Toleubekova, Z., Assylkhanova, A., Balgabayev, N., & Kovács, Z. (2023). Identification of Potential Farm Pond Sites for Spring Surface Runoff Harvesting Using an Integrated Analytical Hierarchy Process in a GIS Environment in Northern Kazakhstan. Water, 15(12), Article 12. https://doi.org/10.3390/w15122258

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Publication Title: Comparison of Climate Change Effects on Wheat Production under Different Representative Concentration Pathway Scenarios in North Kazakhstan
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We: the undersigned co-authors, hereby declare the following:

1. Referring to the publication and the respective sections of the thesis, we confirm that the jointly published results were greatly contributed by the candidate.
2. These results have not been and will not be used by us in the past or in the future for the purpose of acquiring an academic degree or title.

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Publication Title: 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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1. Referring to the publication and the respective sections of the thesis, we confirm that the jointly published results were greatly contributed by the candidate.
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Supervisor's Declaration

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We, the undersigned co-authors, hereby declare the following:

1. Referring to the publication and the respective sections of the thesis, we confirm that the jointly published results were greatly contributed by the candidate.
2. These results have not been and will not be used by us in the past or in the future for the purpose of acquiring an academic degree or title.

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