ABSTRACT

of the dissertation for the degree of Doctor of Philosophy (PhD) in the specialty of 6D075500 - "Hydrogeology and Engineering Geology"
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Implementation of Remote Sensing and GIS in hydrogeological investigations of Makhtaral irrigated lands in the Turkestan region

The relevance of research. The pertinence of this study is underscored by the following factors: In the address of Kazakhstan's Head of State, Kassym-Jomart Tokayev, delivered on September 2, 2019, the imperative of a phased expansion of irrigated land to three million hectares by the year 2030 was articulated, with the overarching objective of augmenting agricultural output by a factor of 4.5. The execution of this presidential directive mandates rigorous monitoring and evaluation of the meliorative state of irrigated lands. Furthermore, Article 15 of Kazakhstan's legislation on State Regulation of the Agro-Industrial Complex and Rural Areas (Law No. 66 of July 8, 2005, amended on November 24, 2021) stipulates that the informational and marketing underpinning of the agro-industrial complex is achieved through the provision of data derived from agrometeorological and satellite monitoring.

In addition, the government's decree, dated December 30, 2021 (No. 960), pertaining to the 'Concept of Development of the Republic of Kazakhstan's Agro-Industrial Complex for 2021-2030,' accentuates the adoption of remote sensing methodologies.

The prevailing circumstances concerning irrigation systems and the degradation of irrigated soils underscore the exigency of devising a regime for vertical and horizontal drainage as well as technological measures to regulate the meliorative state of irrigated lands.

Remote sensing data find extensive application in hydrogeological-meliorative, geological-hydrogeological investigations. The systematic integration of remote methodologies with ground-based observations in pivotal locales augments the informativeness of research endeavors.

For comprehensive investigations within this purview, the Maktaaral region in the Turkestan province has been designated as the primary focal point, as it embodies a rich legacy of over half a century in land reclamation practices and possesses a well-established ethos of irrigated agriculture. Cotton cultivation assumes a pivotal role in the economic dynamics of the Maktaaral district and the nation at large. Although the contribution of cotton fiber to the overall agricultural exports stands at a modest 3.8%, the export of cotton significantly outpaces its import, exceeding it by 21.5%.

The primary objective of this study is to investigate the regional hydrogeological and hydromeliorative characteristics of the Maktaaral Irrigation land using GIS (Geographic Information System) technologies and remote sensing

data. The study aims to assess the potential for using water from vertical drainage wells for land irrigation through numerical modeling.

To achieve this goal, a comprehensive approach is employed, which includes the use of modern remote sensing methods, ground-based route surveys, GIS, and numerical modeling techniques for assessing the hydrogeological conditions of the area.

To achieve the stated objective, the following primary tasks were required to be addressed:

1) A comprehensive analysis of the hydrological, geological-geophysical, and hydrogeological conditions within the study area was conducted. This involved the compilation, analysis, and systematic organization of previous research to refine the understanding of groundwater distribution, as well as the regional patterns governing the formation, movement, and discharge of ground and subsurface water resources in the Maktaaral Irrigation lands;

2) On-ground route surveys were carried out to assess the hydrological dynamics within the research area. This process aimed to enhance our understanding of the chemical composition of groundwater through detailed laboratory investigations;

3) Employing GIS technologies, we identified regions with both favorable and critical meliorative conditions through the analysis of spectral index images;

4) Through the application of regression analysis on spectral indices and multi-spectral satellite imagery from medium-resolution platforms such as LandSat-8 and Sentinel-2, we established the equation for a predictive model of soil salinity. This model is instrumental for further cartographic delineation of soil salinity levels within the irrigated lands of the Maktaaral Irrigation Array;

5) The potential for secondary water usage from vertical drainage wells for irrigation was evaluated, and various scenarios were formulated to assess the influence of water extraction from such wells on the groundwater regime. This was achieved through the application of a numerical model.;

6) A comprehensive calculation of the water balance was conducted based on the implementation of a numerical model.

These tasks were fundamental to the realization of the overarching research objective.

The object of the research encompasses the irrigated lands within the Maktaaral Irrigation Array located in the Turkestan region.

The research subject pertains to the regional characteristics of hydrogeological and hydromeliorative conditions, the hydrological balance, the chemical composition of underground and drainage waters, and the salinity levels in the irrigated lands of the Maktaaral Irrigation Array situated in the Turkestan region.

The research methodology was applied to examine the relationship between crop yield and the hydrogeological conditions of the irrigated areas in the Maktaaral Irrigation Array. This involved collecting and digitizing monitoring data and subsequently comparing it with remote sensing data (ERS). The predictive equation for soil salinity was obtained through regression analysis, utilizing statistical data

from soil salinity measurements and spectral indices and channels extracted from LandSat-8 and Sentinel-2 satellite imagery.

The efficiency of vertical drainage well (VDW) operations, both under current operational practices, in compliance with regulatory standards, and in accordance with project specifications, was assessed through numerical modeling of the hydrogeological conditions within the Maktaaral Irrigation Array.

The primary propositions to be presented for examination are as follows:

The employment of remote sensing data (ERS) combined with an analysis of spectral vegetation indices, salinity indices, and water indices facilitates the evaluation of the influence of soil salinity, groundwater levels, and mineralization on the yield of raw cotton in regions characterized by both favorable and critical meliorative conditions.

The utilization of remote sensing data, in tandem with regression analysis of spectral channels, salinity indices, and data from salinity measurements, permits the establishment of the equation for a predictive model of soil salinity. This model achieves a notably high level of precision, reaching up to 83%, in the mapping of soil salinity within the irrigated lands of the Maktaaral Irrigation Array.

The numerical model depicting the hydrogeological conditions within the irrigated lands offers the capability to forecast these conditions in a variety of scenarios relating to the operation of vertical drainage wells (VDW). The model highlights the inefficacy of the current VDW operation mode and provides the means to identify the most suitable mode for enhancing the meliorative situation. This, in turn, leads to an augmented cotton crop yield within the research area.

The scientific novelty of the study can be summarized as follows:

A new comprehensive approach has been proposed, integrating remote sensing methods, GIS technologies, and mathematical modeling, to examine the influence of hydrogeological conditions in irrigated areas on the crop yield of agricultural crops.

An equation for a predictive model of soil salinity has been identified through regression analysis of spectral channels, salinity indices, and data from salinity measurements. This equation enables the mapping of soil salinity in areas that have not been covered by ground-based salinity monitoring efforts.

Based on mathematical modeling, a scenario for the operation of vertical drainage wells (VDW) has been suggested and justified. This scenario ensures the maintenance of favorable hydrogeological conditions throughout the year, which positively impacts crop yield.

The practical significance of this research lies in the utilization of the research findings, the data analysis and decryption methodology of remote sensing data (ERS), and the creation of scenarios, in conjunction with the application of mathematical models, for the rational use of water resources in irrigation. These findings aim to enhance the cotton crop yield in the Maktaaral Irrigation Array.

The author's individual contribution to this research encompasses the following:

The formulation of the dissertation's objectives and tasks;

The processing, analysis, and decryption of an extensive time-series dataset derived from remote sensing data (ERS);

The execution of ground-based route surveys;

The development of a mathematical model;

The generation of thematic maps utilizing contemporary GIS technologies;

The synthesis and interpretation of the research outcomes;

The articulation of conclusions and fundamental propositions to be presented during the dissertation defense;

Authoring scientific articles on the dissertation's topic.

These actions collectively exemplify the author's substantial engagement and contribution to the research endeavor.

The research results have been widely discussed and validated at international and national scientific forums and seminars. They have been published in 6 articles, including:

2 articles in national specialized publications recommended by the Committee for Education and Science Control of the Ministry of Science and High Education of the Republic of Kazakhstan.

2 articles in an international journal indexed in the Scopus database (THE NEWS of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences).

2 articles published in the proceedings of international conferences.

These publications and validations have ensured the dissemination and recognition of the research outcomes both nationally and internationally.

The dissertation is structured as follows: it includes an introduction, 5 chapters, a conclusion, and a list of references. The total volume of the dissertation comprises 159 pages of text, featuring 54 figures, 18 tables, and a list of references encompassing 110 sources.

Chapter 1. Remote Sensing Methods and Their Application in Hydrogeological and Hydroreclamation Studies.

Remote sensing data have become increasingly important in geological mapping, hydrogeological, engineering-geological, and environmental-geological research. The combination of aerospace methods with ground-based observations on key areas enhances the informativeness of studies.

Remote sensing methods are often used in conjunction with GIS systems, and their combined application allows for weighted overlay analysis, which can identify potential areas with groundwater presence.

In irrigated agriculture, remote sensing methods are primarily employed for precise crop classification, yield analysis, yield forecasting, detection of land salinity and waterlogging, and assessment of vegetation water stress. Spectral vegetation indices, water indices, and salinity indices are used to address these tasks.

The application of multivariate regression methods enables the accurate mapping of soil salinity.

Numerous studies have shown that vertical drainage is an effective means of land reclamation in irrigated areas. Its use can reduce the loss of irrigated land, conserve water resources, create favorable conditions for agricultural activities,

promote intensive farming, and is essential in managing surface water runoff from open drainage networks.

Chapter 2: General Information about the Study Area.

The irrigated lands of the Maktaaral Massif are located in the Turkestan Region on the left bank of the Syrdarya River in the Kazakh part of the Golodnostep massif.

The natural watercourse in the study area is represented by the Syrdarya River, one of the largest rivers in Central Asia, formed by the confluence of the Naryn and Kara-Darya rivers. It flows to the northeast, along the eastern border of the Maktaaral District. The river has a total length of 2,137 kilometers, a maximum flow velocity of 1.65 m/s, and an average flow velocity of 0.9-1.2 m/s. The river's depth ranges from 3.7 to 6.0 meters, with a channel width varying from 160 to 300 meters (at the Kok-Bulak hydrological station).

The study area is situated within the Golodnostep depression, which is associated with the southeastern part of the Syrdarya Syncline. The geological structure, geostuctural features, and tectonics of this region are relatively well-documented in numerous reports and monographic literature concerning the geological structure of the area.

The tectonics of the study area are characterized by its location within the Tashkent Arid Steppe Depression, bounded by the Mansurat Anticline to the north, the southern extension of the Jausumkum-Bel Anticline to the west, the Turkestan and Nurat Anticlines to the south, and the Kuramin, Kyzyl-Nura-Aktash, and Ugam-Karzhantau Mega-Anticlines to the east.

The geomorphology of the study area is relatively simple, with an accumulation type of relief being predominant based on genetic features. The entire area is occupied by forms of accumulated relief and is represented by three complexes of river terraces (low, medium, and high).

Hydrogeologically, the study area is located in the southeastern part of the complex artesian and artesian-piezometric basin of the Syrdarya River. It is part of the Arid Steppe Depression, which is part of the Prityashkent Basin.

The artificial network of irrigation canals covering the entire Arid Steppe region contributes to the recharge of the first near-surface aquifers due to filtration losses.

Chapter 3: The BIOWAT Project and Spectral Indices in Areas with Favorable and Critical Conditions.

The classification of satellite imagery of the irrigated areas based on the cultivated crops through spectral analysis is an applicable method.

The melioration situation in the Golodnostep Massif is less than satisfactory. An area with elevated groundwater levels is observed in the central and southeast parts, while groundwater mineralization is high in the central and northwest parts. Vertical drainage wells have a limited impact on the melioration status of the irrigated massif.

Spectral vegetation indices, such as SAVI and NDVI, are more informative than other indices (MSAVI2, GEMI, ARVI, IPVI, MTVI, TDVI) under critical and favorable melioration conditions in the Golodnostep Massif.

Vegetation indices of cotton fields within areas with favorable melioration conditions are higher than the values of vegetation indices of cotton fields within areas with critical melioration conditions. The difference in the values of vegetation indices allows us to infer that in areas with favorable melioration conditions, the cotton crop yield exceeds the yield of cotton in areas with critical melioration conditions by a minimum of 10% or 2.6 c/ha.

The amplitude of variation during the year in the NDWI water index is higher than in MNDWI, making it more informative. In areas with favorable conditions, the values of water indices NDWI and MNDWI are significantly lower (by 15-25%) than in areas with critical melioration conditions.

The NDSI salinity index in critical and favorable melioration conditions of the Golodnostep Massif does not exhibit a linear correlation with field soil salinity data. However, the NDSI values of cotton fields under favorable conditions are significantly lower (by 18%) than in areas with critical conditions. The lack of a strong correlation between NDSI and field soil salinity data can be attributed to multiple factors influencing spectral characteristics (different land cultivation periods, different irrigation times, various agricultural crops, etc.).

Chapter 4. Regression Analysis of Spectral Indices and Channels of Medium-Resolution Multispectral Satellite Images for Mapping Soil Salinity in the Irrigated Lands of the Maktaaral Array.

Indices of salinity, when used individually or as various multispectral image channel composites, are inefficient for mapping soil salinity in the irrigated lands. Regression analysis, which allows for establishing the relationship between the dependent variable (soil salinity data) and independent variables (spectral channels and salinity indices of LandSat-8 and Sentinel-2), has demonstrated good efficacy in mapping soil salinity in the Maktaaral Array of irrigated lands. The maximum level of accuracy was achieved using the LandSat-8 image (LC08_L1TP_154032_20210425_20210501_01_T1) dated April 25, 2021, which resulted in a correlation coefficient of $r^2 = 0.83$. The derived equation is as follows:

PMZP = 3.49 - 19.16 * band1 + 13.33 * band2 - 0.36 * band3 + 33.72 * band4 + 2.48 * band5 - 5.25 * band6 - 0.49 * band7 - 3.83 * band8 - 141.4 * band9 + 4.69 * NDSI + 4.44 * SI14 + 3.55 * SI10 - 14.01 * SI9 + 38.5 * SI4 - 11.78 * SI2 - 40.6 * SI1

This coefficient is 10% higher than the maximum correlation coefficient of $r^2 = 0.73$ obtained from Sentinel-2 images (L1C_T42TVL_A021653_20210429T061639) dated April 29, 2021.

As of April 25, 2021, the irrigated lands of the Zhetysay District have the following levels of salinity:

Non-saline: 10% or 10,105 ha

Low salinity: 35% or 35,390 ha

Moderate salinity: 40% or 40,598 ha

High salinity: 14% or 14,213 ha

Saline patches: 0.1% or 1.5 ha

The degree of salinity in the Maktaaral District appears as follows:

Non-saline: 7.5% or 5,895 ha

Low salinity: 24.8% or 19,374 ha

Moderate salinity: 54% or 42,720 ha

High salinity: 13% or 10,202 ha

Saline patches: 0.01% or 0.2 ha.

The areas with unfavorable conditions (strongly saline soils and saline patches) in the Maktaaral Array of irrigated lands from 2013 to 2021 exhibit a relatively stable trend, accounting for 17-25% of the total area in the regions.

Chapter 5. Mathematical Model of Hydrogeological Conditions in the Irrigated Lands of the Maktaaral Array.

The objective of the modeling was to assess the efficiency of the existing vertical drainage system (VDW) in the Maktaaral Array, reproduce the recommended operational regimen during flushing, vegetative and non-vegetative periods, and determine the optimal parameters and irrigation schemes.

The components of the water balance in the Maktaaral Array of irrigated lands were determined.

Zones most susceptible to salinity were identified.

Predictive tasks were solved for three scenarios of the vertical drainage system operation.

The inefficiency of the existing system and the system corresponding to the recommended operational regimen was confirmed.

An efficient operation system for vertical drainage was selected.

To obtain more precise forecasts of changes in hydrogeological conditions resulting from the operation of the vertical drainage system, it is recommended to create local models at critical sites based on the regional model developed.

The potential for secondary water uses from the VDW for sub-irrigation is estimated at 14% of the irrigation norm or 73 million m^3 of additional water source for irrigating 147,102 ha of fields.

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