

Use of Remote Sensing Data for the Rational Use of Precipitation and Meltwater in the East Kazakhstan Region

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Abstract

The article addresses the pressing issue of water security, which has emerged as a significant global risk in the 21st century. With the annual increase in water resource demands due to population growth and socio-economic factors, Kazakhstan faces unique challenges related to its geographical position and reliance on transboundary rivers. Eastern Kazakhstan is one of the most water-rich regions in the country, featuring the Irtysh River and numerous tributaries. Meltwater annually causes flooding, resulting in significant damage, while its potential remains underutilized in agriculture. In this study, remote sensing technologies were applied through the processing of satellite imagery from NOAA, TERRA, AQUA, Sentinel-1, and Sentinel-2 for the period 2017–2022 to analyze flood events. A digital terrain model (DTM) was constructed to delineate watershed areas. The results indicate that floods are primarily associated with spring snowmelt and predominantly affect regions such as Abai, Ayagoz, and Zaysan, with a potential inundation area of up to 468,9 km². To address these issues, the article proposes the creation of reserve reservoirs to manage surface runoff and drainage from temporarily flooded areas. Research has identified 12 potential sites for the creation of reservoirs, which will not only minimise flood damage but also make effective use of meltwater. This strategy not only reduces flood risks but also improves the availability of water resources for agriculture during dry periods. The results show that the use of modern technologies can significantly improve water resource forecasting and management, which in turn contributes to food security and sustainable natural resource use in a changing climate.

1. Introduction

Water security is one of the major global risks of the 21st century. Each year, humanity's demand for water resources increases by approximately 1% due to the combined impact of factors such as demographic growth, socio-economic development, and changing consumption patterns. For Kazakhstan, water security poses a particular challenge, given a number of factors: the country's geographical location, its dependence on transboundary rivers, the deterioration of the environment, and local climate change.

Floods and inundations are among the major natural hazards, posing risks not only to infrastructure facilities, cities, enterprises, and roads, but primarily to agriculture (Zhao et al., 2018, Conitz et al., 2021, Ha et al., 2023, Apshikur et al., 2023). The flooding of fields, the destruction of dams of reservoirs and ponds used for irrigation as a result of overflows and overfilling, as well as the threat of hydraulic engineering accidents, can and do cause enormous damage (Ballesteros-Canovas et al., 2015). At the same time, a vast amount of water during flood events flows away through the river network, although it could potentially be stored and used for irrigation during dry periods following spring floods.

Meltwater formed as a result of snow and ice thawing represents a significant resource that can be utilized for various purposes, such as agriculture, irrigation, energy production, and other types of water use. However, improper management of meltwater can lead to flooding and other environmental problems (McClung, D. M., 2016).

For the effective use of meltwater, aimed at minimizing potential risks as well as ensuring its accumulation, regulation, and diversion, it is necessary to establish reserve reservoirs.

In this regard, the study (Teleubay et al., 2023) can be noted, which investigated the collection of meltwater and floodwater in a steppe region of Northern Kazakhstan for further use in agriculture. The authors applied remote sensing methods and the Analytical Hierarchy Process (AHP) based on Geographic Information Systems (GIS) to assess potential reservoir sites with an accuracy of 82%. The research was based on six thematic layers: hydrogeology (5%), slope (10%), drainage density (25,5%), land use/land cover (25,5%), soil (5%) and snow water equivalent (29%), which primarily influence the availability, runoff, infiltration, and accumulation of meltwater and floodwater, in order to identify potential reservoir sites in the Akkayin district.

Modern methods and technologies of remote sensing of the Earth, such as satellite imagery, the creation of accurate digital elevation models, and digital modeling of floodwater dynamics, serve as a valuable complement to existing techniques for monitoring water levels in reservoirs and snow cover (Marshall, S. et. al., 1994, Bilasco et. al., 2022, Munawar et. al., 2022, Ali et. al., 2020). These approaches enable the rational use of meltwater by providing accurate and timely flood forecasts, calculating meltwater volumes, and subsequently accumulating this water in designated reservoirs. In turn, this makes it possible to use the full volume of water more efficiently, transform the threat of floods into an advantage, and ensure the most rational and sustainable water use (Tessema, B.H. et. al., 2024).

The purpose of this study is to conduct satellite monitoring of floods and inundations in the territory of the East Kazakhstan region, as well as daily monitoring of snowmelt during the spring period using satellite imagery acquired from TERRA and AQUA (MODIS), Sentinel-1/2, Landsat, Suomi NPP, and other spacecraft.

The practical outcome of this study is the identification of floodwater accumulation zones, inundated areas, and the determination of prospective sites for storage reservoirs, taking into account the terrain features for the construction of dams and embankments. The accumulated water can subsequently be used for the irrigation of agricultural lands and other purposes, including the establishment of fire reservoirs in areas most prone to wildfires, such as forest enterprises, national parks, and related territories.

2. Research area

The study area selected for this research is the East Kazakhstan Region, characterized by a large number of hydraulic structures (Rakhymberdina et al., 2022), complex terrain, and extensive agricultural lands. The East Kazakhstan Region covers an area of 97,8 thousand square kilometers and is one of the most water-abundant regions of Kazakhstan. The Tarbagatai and Chingiztau mountain ranges form the watershed of the region. The main river is the Irtysh, with its primary tributaries being small rivers such as the Bukhtarma, Uba, Ulba, Char, Kyzylsu, and Kurchum (Electronic Resource). The rivers of the Kazakh Uplands are generally low-water, highly dependent on precipitation and seasonal variations, with flow regimes ranging from floodwaters to intermittent streams. In addition, there are about a thousand large and small lakes in the region. Lakes are distributed unevenly, with most concentrated in the Irtysh River basin and its tributaries, as well as in the high mountain areas near the Berel glaciers. The largest lakes in East Kazakhstan are situated in river valleys and intermountain depressions, such as Markakol, Alakol, and Sasykkol. The most significant lakes are Zaysan, Markakol, Alakol, and Sasykkol. In the territory of East Kazakhstan (Southwestern Altai), there are over 360 glaciers with a total area of 99,4 km². The largest of these are the Great Bukhtarma and Small Bukhtarma glaciers. The water resources of East Kazakhstan consist of 1017 rivers with a total length of about 28 000 km and an average annual flow of approximately 30 billion m³; 1968 lakes with a combined water volume of around 6,5 billion m³ (excluding Lakes Alakol and Sasykkol); 219 reservoirs and small ponds; and three major reservoirs: the Ust-Kamenogorsk, Bukhtarma, and Shulbinsk reservoirs (Toguzova M.M., et.al., 2024).

The climate of the East Kazakhstan Region is highly diverse. Alongside vast plains, steppes, semi-deserts, and deserts, the territory also includes extensive foothills and high mountains, where mountain ranges alternate with intermountain basins and valleys. Climatic conditions vary significantly between lowland and mountainous areas, both in terms of temperature and precipitation. The sharp continentality of the desert and semi-desert zones is considerably moderated in the foothills and mountainous regions. Winter is cold and prolonged, with January being the coldest month. The average monthly temperature ranges from –12°C to –17°C, and in some areas drops to –23°C to –27°C. Absolute minimum temperatures may reach –51°C to –54°C. In contrast, summers are warm, with July average temperatures ranging from 15°C to 24°C, while absolute maximums can reach 35°C to 45°C. In the mountains, summer temperatures strongly depend on elevation. The warm period, defined by daily average temperatures above 0°C, lasts less than 200 days in the northeast (mountainous and foothill areas) and between 200 and 230 days in the southern part of the region (steppe, semi-desert, and desert areas). Precipitation is distributed unevenly across the region. In the northeast, annual precipitation reaches 400–650 mm (mountainous and foothill areas), while in intermountain basins it drops below 200 mm per year. Precipitation during the warm season dominates over the cold season, with a maximum occurring in summer, particularly

in the second half of the season. Despite this, meltwater continues to cause annual damage while remaining largely underutilized for agricultural and economic purposes (Rakhymberdina et al., 2025).

3. Data and Methodology

3.1 Current status of hydrological monitoring and flood forecasting

Currently, flood monitoring in the territory of East Kazakhstan Region is carried out through a combination of stationary hydrological posts located on water bodies and hydrogeological networks, snowpack observations obtained from snow survey stations, precipitation data from stationary meteorological stations of the national service “Kazhydromet” (Electronic Resource) as well as satellite monitoring conducted by the private company GEOSAT (Fig. 1). All measurements at the hydrological posts of RSE “Kazhydromet” are generally performed manually at the observation points. Under normal conditions, water level is measured using instrumental methods at least twice per day (08:00 a.m. and 08:00 p.m. local time). During the flood season, the frequency of measurements increases and the time interval between them is reduced (every 6 h, 4 h, 2 h, or even hourly), depending on the rate of water level rise or decline. Measurement data are recorded in a dedicated observation log and transmitted via radio or telephone communication. In rare cases, a limited number of hydrological stations are equipped with RiverRay acoustic Doppler current profilers, which allow data transmission via mobile networks and the Internet. For hydrological situation monitoring and flood risk assessment in East Kazakhstan Region, GEOSAT employs modern Remote Sensing (RS) technologies, including the acquisition and thematic processing of satellite imagery from TERRA and AQUA (MODIS), as well as the LANDSAT and SENTINEL series. The company develops thematic maps and provides data through a specialized GIS-based service. Thematic maps are distributed via e-mail to governmental agencies, departments, and institutions responsible for decision-making in the case of emergencies. These materials are further used for damage mitigation, coordination of local populations and emergency services, and in recovery and disaster response activities.

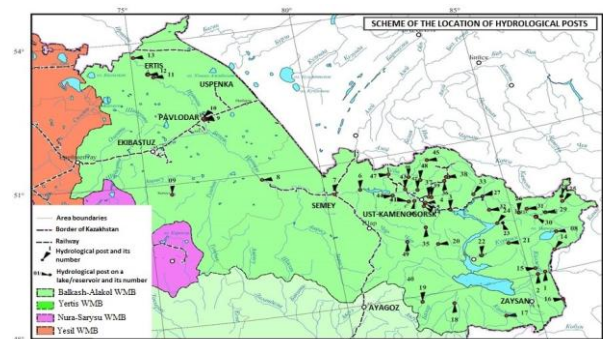


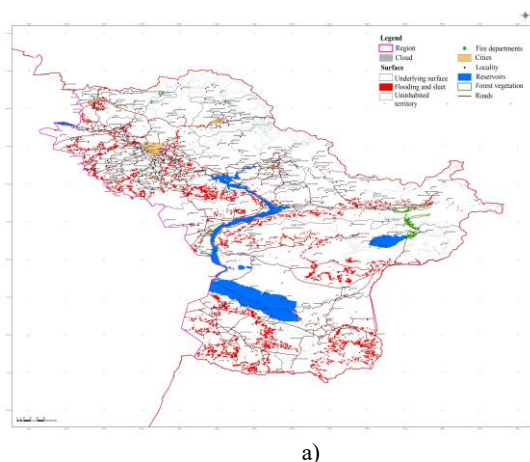
Figure 1. Hydrometric Station Network in the Region.

3.2 Collection for Floodwater Storage Management

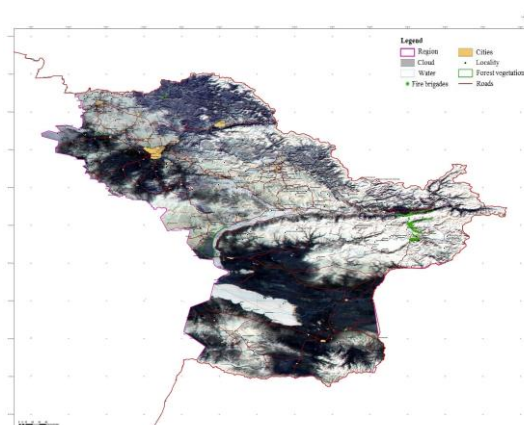
For this study, an analysis was conducted of data from ground-based stations regarding precipitation in the study areas, snow survey results, and the dynamics of surface water in the hydrological network and water bodies of the region for the period 2020–2023. Archival satellite imagery of the region from TERRA and AQUA (MODIS), as well as the LANDSAT series,

was also examined. The collected data were used to create maps with classified areas, including flood zones, snow cover boundaries, wet soil, dense snow, open water surfaces, snowmelt areas, and other relevant features for the period 2020 - 2023.

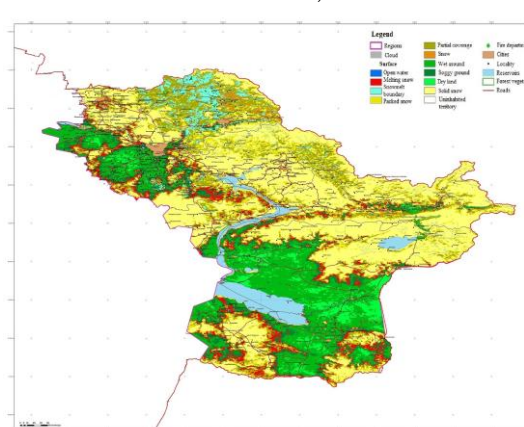
Satellite data from TERRA and AQUA (NASA) are equipped with the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor, which provides daily information on snow cover fraction and surface water at a spatial resolution of 250–1000 m. These data allow for the assessment of snow water equivalent, monitoring of snowmelt, and flood detection through analysis of surface water changes. LANDSAT satellite data (NASA/USGS) complement MODIS with higher spatial resolution (30 m), suitable for detailed mapping of flooding and snowmelt at local scales. The datasets are combined to improve accuracy using spectral indices (e.g., NDWI, MNDWI) and machine learning models. MODIS onboard TERRA and AQUA generates 8-day composite snow cover products (MOD10A2.006 for TERRA, MYD10A2.006 for AQUA). To reduce errors caused by cloud cover and sensor angle (overestimation: 46%, underestimation: 3,66%), seasonal (winter/summer), temporal (cloud pixel replacement with neighboring images), and spatial filters were applied. Integration of TERRA and AQUA data with the Randolph Glacier Inventory 6,0 tool produced an enhanced MOYDGL06* product, improving accuracy by 10% (up to 87% validated against LANDSAT-8). This enables reliable estimation of snow water equivalent, which is crucial for East Kazakhstan, where snowmelt contributes significantly to river runoff. LANDSAT data were used for high-resolution snowmelt mapping employing spectral indices (NDWI for water surfaces) and temporal series analysis. Combined with MODIS, these datasets provided comprehensive information on snow cover dynamics (Fig. 2a). Time series analysis of MODIS data was performed using SARIMA (Seasonal Autoregressive Integrated Moving Average) following the Box–Jenkins methodology, supporting snow water storage and melt forecasting. Flood monitoring was conducted using daily MODIS imagery from TERRA and AQUA. Application of the MNDWI (Modified Normalized Difference Water Index) enabled flooded area detection with an accuracy of 97%. Integration with DEM (Digital Elevation Models) further enhanced flood risk maps, especially in the mixed landscapes characteristic of East Kazakhstan. For detailed inundation mapping, the DSWE (Dynamic Surface Water Extent) model was applied (Fig. 2b, 2c).



a)



b)



c)

Figure 2. Development of Thematic Maps Based on DEM: a) Thematic map of flood and wet snow zones in East Kazakhstan region according to MODIS (TERRA) data for 03/25/2023 (shooting time 04:55 UTC); b) Thematic map of ice-water hospitals in East Kazakhstan region according to MODIS (TERRA) data for 03/25/2023 (shooting time 04:55 UTC); c) Thematic map of snow cover and snowmelt boundaries of East Kazakhstan region according to MODIS (TERRA) data for 03/25/2023 (shooting time 04:55 UTC)

A Digital Elevation Model (DEM) of the region was constructed to determine the catchment areas (Fig. 3).

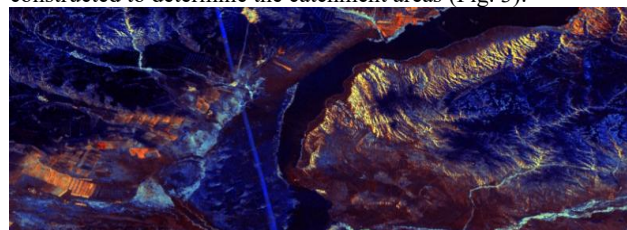


Figure 3. Fragment of a digital terrain model of the region.

The normalized difference water index was calculated to identify flood-prone areas in Eastern Kazakhstan (Bukhtarma reservoir, Kurchum, Markakol districts (Fig. 4a), Ulken-Naryn and Katon-Karagai districts (Fig. 4b), Shulbinsky reservoir, Ulan, Glubokoe districts (Fig. 4c), Lake Zaisan, Tarbagatai district (Fig. 4d), Ulan district (Fig. 4e)) based on the following input data: digital elevation model and shapefile of the area of

interest based on Landsat 8 OLI/TIRS C2 L2 Imagery Tiles (Band 3 & Band 5 Tiles) data (Fig. 4).

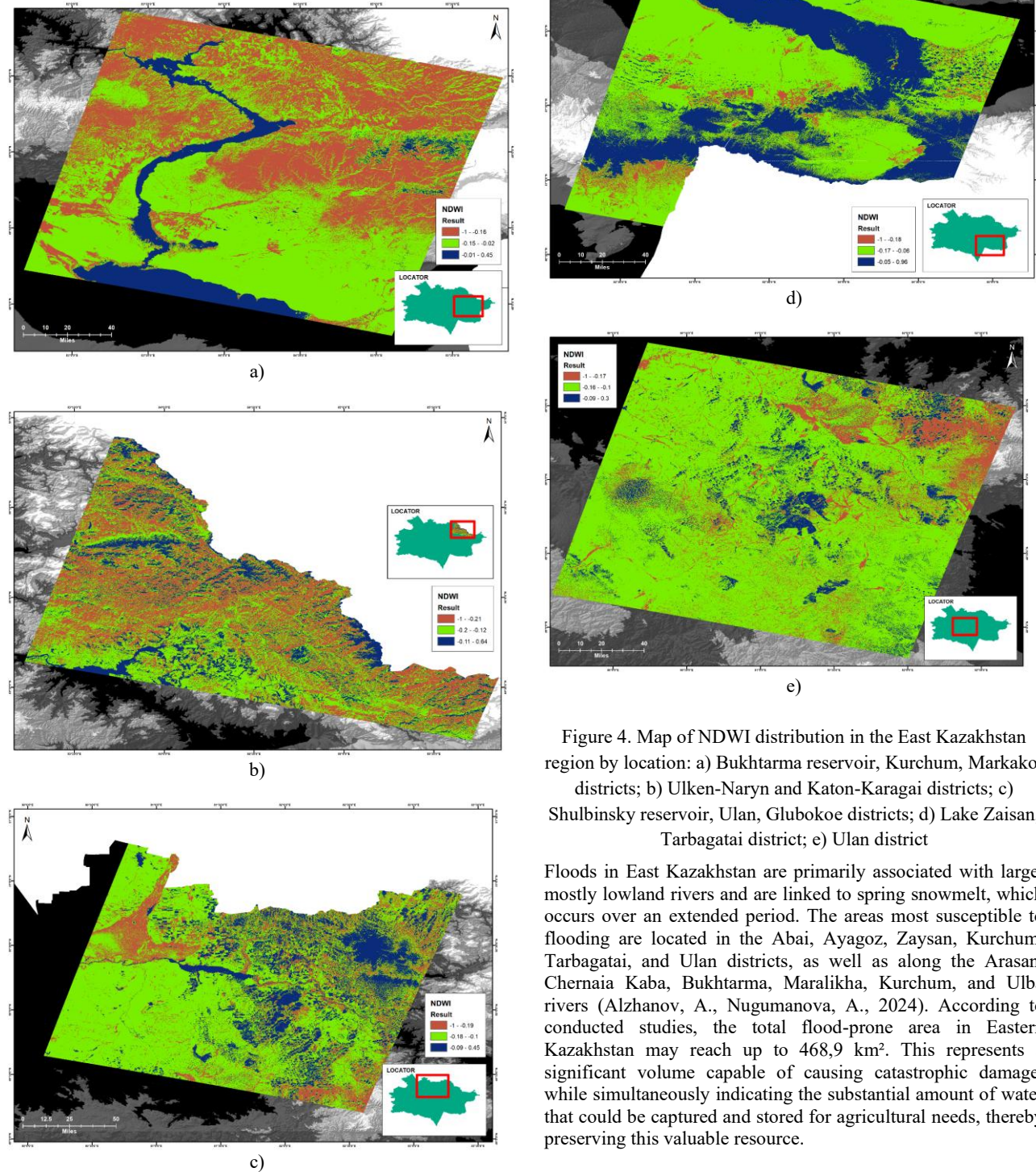


Figure 4. Map of NDWI distribution in the East Kazakhstan region by location: a) Bukhtarma reservoir, Kurchum, Markakol districts; b) Ulken-Naryn and Katon-Karagai districts; c) Shulbinsky reservoir, Ulan, Glubokoe districts; d) Lake Zaisan, Tarbagatai district; e) Ulan district

Floods in East Kazakhstan are primarily associated with large, mostly lowland rivers and are linked to spring snowmelt, which occurs over an extended period. The areas most susceptible to flooding are located in the Abai, Ayagoz, Zaysan, Kurchum, Tarbagatai, and Ulan districts, as well as along the Arasan, Chernaya Kaba, Bukhtarma, Maralikh, Kurchum, and Ulba rivers (Alzhanov, A., Nugumanova, A., 2024). According to conducted studies, the total flood-prone area in Eastern Kazakhstan may reach up to 468,9 km². This represents a significant volume capable of causing catastrophic damage, while simultaneously indicating the substantial amount of water that could be captured and stored for agricultural needs, thereby preserving this valuable resource.

3.3 Identification of sites for constructing floodwater storage reservoirs

The areas most at risk are Glubokovsky, Altai, Kurchum, Samarsky, Tarbagatai, Shemonaiha, Katon-Karagai, Ulken Naryn, and Markakol districts. Based on the conducted studies, 12 sites were identified for the construction of floodwater storage reservoirs. The selection of these sites was guided by several criteria: proximity to floodwater pathways, terrain characteristics to minimize the use of mechanized equipment for constructing artificial reservoirs, proximity to agricultural lands

requiring irrigation or substantial water volumes for industrial purposes, and, in some cases, locations with a high likelihood of natural forest and steppe fires, such as in the Tarbagatai, Samarsky, Katon-Karagai, and Ulken Naryn districts (Fig. 6). The analysis of natural fires was carried out for the period from 2015 to 2024. The data were obtained from the archive of the Operational Monitoring Center of GEOSAT LLP and included information from the satellites Aqua, Terra, Suomi-NPP, NOAA-20, MetOp-A, MetOp-B, MetOp-C, Sentinel-3A, Sentinel-3B, Sentinel-2A, Sentinel-2B, Landsat-8, and Fengyun-3D. A large number of natural fires were recorded across the region, with the highest numbers occurring in 2017 (563 forest fires), 2018 (358 forest fires), 2019 (628 forest fires), and August 2020 (484 forest fires). These fires often occurred in remote areas far from the hydrological network, complicating firefighting efforts and post-fire recovery (Fig. 5). This evidence highlights the urgent need to construct floodwater storage reservoirs.



Figure 5. Natural Fires in the Territory of East Kazakhstan Region.



Figure 6. Prospective Sites for Constructing Floodwater Storage Reservoirs.

4. Results and discussion

As a result of the conducted research on flood and inundation monitoring, snowpack monitoring, and monitoring of natural forest and steppe fires, the following outcomes were obtained:

- A digital elevation model (DEM) was created to monitor floodwater runoff and determine inundation zones in the East Kazakhstan region; elevation matrices were generated based on remote sensing data, and optical satellite imagery from TERRA, AQUA (MODIS), LANDSAT, Sentinel, Suomi-NPP, NOAA-20, MetOp-A, MetOp-B, and MetOp-C was acquired and processed.
- Data from hydrological stations across the region were analyzed.
- Thematic maps of flood-prone zones were developed, as well as maps indicating prospective sites for constructing floodwater storage reservoirs, taking into account the irrigation needs of agricultural lands.

- A multi-year analysis of natural forest and steppe fires was conducted based on satellite imagery.

- Thematic maps were created indicating prospective sites for constructing floodwater storage reservoirs, considering areas most prone to natural forest and steppe fires.

The application of modern remote sensing methods and technologies, combined with GIS systems and traditional ground-based meteorological observations, enables the rational use of meltwater through accumulation, regulation, and management of surface runoff and drainage from flooded, temporarily inundated, irrigated areas, and lowland disturbed lands. This approach not only allows for the prediction of potential floods and inundations and the modelling of floodwater dynamics but also facilitates the practical use of floodwaters for accumulation and subsequent utilization in agriculture, forest management, and other sustainable natural resource applications. The accumulation of floodwaters can address local-scale issues and has the potential to transform approaches to transboundary rivers and reservoirs, minimize risks under changing climate conditions, and support national and food security objectives.

4. Conclusions

The study yielded significant results concerning the monitoring of floods and snow reserves, as well as the impact of climate change on water resources in East Kazakhstan.

The use of TERRA and AQUA (MODIS) satellites provided data on snow cover, which was processed to estimate the water equivalent of snow. These data showed that the average snow cover in the region varied from 50 to 150 mm depending on the altitude and season. The analysis found that maximum reserves were observed in mountainous areas, confirming the importance of this information for forecasting spring snowmelt and potential flooding.

The development of digital elevation models and thematic maps made it possible to accurately delineate flood-prone zones, which were identified in areas such as Abai, Ayagoz, and Zaisan. The total potential inundation area reached up to 468.9 km², indicating a considerable risk to agricultural land and infrastructure. The application of indices such as MNDWI ensured high precision in detecting flooded areas, achieving an accuracy of up to 97%.

Based on the collected data, 12 promising sites were identified for the construction of water retention reservoirs. These sites were selected considering their proximity to floodwaters, terrain characteristics, and agricultural needs. The findings suggest that the establishment of such reservoirs would not only reduce flood risks but also provide an additional water resource for irrigating agricultural land during dry periods.

The analysis of wildfire data in the region from 2015 to 2024 revealed that the majority of fires occurred in areas remote from water sources, which significantly complicated firefighting efforts. This highlights the urgent need to establish water retention reservoirs that could serve as reliable sources of water for wildfire suppression.

The findings confirm that integrating remote sensing methods with traditional monitoring enables more effective water resource management and reduces risks associated with floods. The combination of technologies such as satellite imagery and GIS opens new horizons for the study and management of water resources.

The results of the research emphasize the importance of a comprehensive approach to addressing water security challenges, including collaboration among various stakeholders. Such an approach would not only enhance forecasting and monitoring capabilities but also contribute to the development

of sustainable water management solutions in the context of climate change.

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