**ABSTRACT**
to the PhD Dissertation for the Degree of Doctor of Philosophy (PhD) in Specialty 6D071100 – Geodesy

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**IMPROVING THE METHODOLOGY FOR MONITORING ICE MOVEMENT IN THE CASPIAN SEA USING REMOTE SENSING TECHNOLOGIES**

This dissertation research addresses the critical issue of monitoring ice movement in the Caspian Sea using advanced remote sensing technologies. Given the increasing interest in hydrocarbon exploration and extraction in this region, particularly on the North Caspian shelf, oil companies face numerous technical and environmental challenges. These challenges stem from the region's unique natural features, which significantly impact the planning and execution of drilling operations, as well as the design and maintenance of offshore facilities.

A key factor influencing the operation of marine facilities is the significant seasonal temperature fluctuations: temperatures can reach 40°C in summer and drop to -30°C in winter. Such extreme conditions require accurate and up-to-date ice condition maps to ensure the safety and efficiency of maritime operations. Ice load poses a serious threat to offshore structures and pipelines, as ice tends to move, creating risks of piling up in front of structures, overtopping them, or shifting them from their foundations.

**Objectives and Tasks of the Research**

The main goal of this research is to develop a technology and methodology for monitoring ice movement using remote sensing data. To achieve this, the following tasks were set:

- Analyze existing methods and data for monitoring sea ice movement.
- Enhance shoreline mapping technology to determine the ice-covered area using a geospatial analysis model.
- Optimize supervised classification methods for identifying ice formations using remote sensing data.
- Develop a geospatial analysis model to forecast ice movement based on remote sensing data.

**Research Methods**

To accomplish the tasks, the study used remote sensing methods, including data analysis from various satellite platforms such as ENVISAT, Aqua MODIS, and Sentinel 1A. Geospatial analysis techniques, image segmentation, and supervised classification were also employed. In addition, mathematical models were developed to account for ice dynamics under climate and meteorological influences.

**Results**

The research showed that a comprehensive approach incorporating data from multiple satellite platforms overcomes the limitations associated with incomplete

information from a single source. The developed methodology for integrating multi-temporal satellite data ensures high accuracy in reconstructing ice conditions.

A new technological solution for shoreline mapping and ice classification was developed and tested, utilizing both historical and recent data. Optimizing parameters for a digital elevation model of the seabed significantly improved the accuracy of visualizing and analyzing topographic changes caused by ice cover.

Expanding the data spectrum by incorporating additional information from platforms like Sentinel-3, MODIS, ENVISAT, and SAR systems increased the frequency and variety of observations. This approach proved to be a key factor in improving the accuracy of ice movement forecasts, leading to both quantitative and qualitative improvements in monitoring procedures.

However, analysis revealed that existing ice movement models have yet to achieve full automation and still require expert intervention to correct errors. Therefore, the dissertation justifies the need for further development of artificial intelligence and machine learning algorithms and emphasizes enhancing data verification procedures to minimize manual control and increase system autonomy.

**Scientific Novelty**

The scientific novelty of this research includes the following:

1. An enhanced supervised classification method for detecting ice formations in remote sensing data based on segmentation, which improves the geometric accuracy of identified objects.
2. A technology for monitoring ice movement based on spatial-temporal changes in objects derived from remote sensing data, enabling the identification of ice drift zones.
3. A geospatial analysis model for studying sea ice to forecast ice movement based on remote sensing materials.

**Key Scientific Propositions**

The following scientific propositions are presented:

1. Mapping of ice formations and precise boundary determination are achieved using multispectral and hyperspectral data. Image segmentation is based on reflectance differences between ice and water types, as well as dielectric properties and surface roughness of ice and water observed in radar data.
2. Identification of ice drift zones and tracking of its dynamics are performed using a trained model to automatically determine pixel intensity over time and the movement vector and velocity components along the x and y axes.
3. Forecasting the dynamics and direction of ice movement is conducted using Kriging interpolation on integrated multi-temporal data, time series analysis, and map generation with subsequent dynamic modeling of ice masses.

**Practical Significance**

The practical significance of this work includes:

- Improved shoreline mapping technology using a geospatial analysis model, enabling the determination of the ice-covered area in the study region.

- Development of a technological scheme for monitoring ice movement based on remote sensing data.
- Creation of practical guidelines for using supervised classification methods for ice condition monitoring, which can be utilized by emergency services, navigational, and oil companies in the northeastern Caspian Sea.
- Investigation of the impact of ice conditions on seabed topography, substantiating the choice of interpolation method for depths and cell sizes for constructing a digital model of the seabed topography.
- Creation of a library for classifying ice types.

**Validity and Reliability**

The validity and reliability of scientific propositions, conclusions, and recommendations are confirmed by a large volume of primary data spanning from 2000 to 2022, as well as by good convergence of prediction results with actual data. The author's contribution includes studying and analyzing domestic and international experience in organizing sea ice movement monitoring, improving shoreline mapping technology to determine the ice-covered area using a geospatial analysis model and supervised classification methods for identifying ice formations from remote sensing data, and investigating mathematical models for forecasting ice movement.

**Publications and Approvals**

Based on the dissertation work, eight publications were made, including:

- One article in the rated journal *Geodesy and Geodynamics* (Scopus Q2).
- Three articles in journals recommended by the Ministry of Education and Science of the Republic of Kazakhstan (MES RK).
- Four articles in proceedings of international conferences, forums, and congresses.

The classification methodology was applied at LLP "Institute of Ionosphere," and the ice type library was used to study ice conditions in the Caspian Sea using remote sensing data. The research results were implemented in the educational process, confirmed by relevant records.

**Conclusions**

The monitoring of ice movement should be carried out using remote sensing methods, which allows for extensive coverage of the study area. Due to the lack of images obtained from a single platform, data from satellites ENVISAT, Aqua MODIS, and Sentinel 1A must be used together. A methodology and technology based on multi-temporal data were developed for effective monitoring. Ice identification requires additional verification through other satellite data, such as Sentinel-3, MODIS, Landsat, and various SAR platforms.

Based on the conducted research and developments, the following conclusions can be drawn:

1. **Technological improvement in shoreline mapping**:
   - The implementation of a geospatial analysis model significantly improved the shoreline mapping process, enabling precise determination of the ice-covered area. This allows for more detailed and accurate monitoring of changes in ice conditions.

2. **Monitoring ice movement**:

- The developed technological scheme for monitoring ice movement based on remote sensing data enables effective tracking of ice mass dynamics, which is essential for risk management associated with ice conditions.

3. **Practical guidelines for supervised classification**:

- The creation of guidelines for supervised classification methods for ice condition monitoring provides a valuable methodological basis for emergency services, navigational, and oil companies. These methods are particularly useful for work in the northeastern Caspian Sea, where ice conditions significantly affect operational safety and efficiency.

4. **Impact of ice conditions on marine topography**:

- The study of ice conditions' impact on seabed topography revealed the need for careful selection of interpolation methods for depths and cell sizes in constructing digital seabed models. Proper selection of these parameters ensures a more accurate seabed representation, essential for navigation and marine research.

5. **Creation of an ice classification library**:

- The development of a specialized library for classifying different ice types enhances the accuracy of ice condition analysis and interpretation, which is critical for applications including scientific research, industry, and maritime safety.

These conclusions underscore the importance and effectiveness of implementing modern geospatial technologies and analytical methods for monitoring and managing ice conditions. These developments not only improve the accuracy and efficiency of existing methods but also provide new tools for research and practical applications in various fields.

**Structure and Volume of the Dissertation**

The dissertation consists of an introduction, three chapters, a conclusion, and a bibliography. It is presented on 110 typed pages, contains 15 tables, 61 figures, and a bibliography with 133 references.