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Digital design of measurement equipment for geodynamics and seismicity in the Azerbaijani sector of the Caspian Sea

Cyfrowe projektowanie aparatury pomiarowej do badań geodynamiki i sejsmiczności w azerskim sektorze Morza Kaspijskiego

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ABSTRACT: This study presents the digital design of equipment for high-precision monitoring of geodynamic and seismic processes in the Azerbaijani sector of the Caspian Sea and its adjacent coastal zones. The research area includes the Absheron Peninsula, Gobustan, Shamakhi, Lankaran, and the marine aquatory covering active tectonic fault zones. The methodology is based on the integration of seismic event data, GNSS and InSAR measurements, geological-tectonic maps, and technical metadata of the existing seismic network. QGIS, ArcGIS Pro, Leaflet.js, and CesiumJS platforms were employed for data processing and visualization. Fuzzy logic was applied for risk assessment, while artificial neural networks (ANNs) were used for optimal station placement. As a result, a prototype system was developed that collects data in real time, automatically updates seismic hazard maps, and provides operational decision support for emergencies. The proposed digital design holds significant practical importance for enhancing seismic safety and continuous monitoring of geodynamic processes in the Republic of Azerbaijan.

Keywords: geodynamic monitoring, seismicity, Caspian Sea, Azerbaijani sector, digital design, seismometer, hydroacoustic monitoring, satellite observations, offshore monitoring systems, data fusion.

STRESZCZENIE: W niniejszej pracy przedstawiono cyfrowe projektowanie aparatury przeznaczonej do precyzyjnego monitorowania procesów geodynamicznych i sejsmicznych w azerskim sektorze Morza Kaspijskiego i przyległych strefach przybrzeżnych. Obszar badań obejmuje Półwysep Apszeroński, rejony Gobustanu, Szemachy i Lenkoranu, a także akwen morski pokrywający aktywne strefy uskoków tektonicznych. Metodyka opiera się na integracji danych dotyczących zdarzeń sejsmicznych, pomiarów GNSS i InSAR, map geologiczno-tektonicznych oraz metadanych technicznych istniejącej sieci sejsmicznej. Do przetwarzania i wizualizacji danych wykorzystano platformy QGIS, ArcGIS Pro, Leaflet.js oraz CesiumJS. Do oceny ryzyka zastosowano logikę rozmytą, natomiast do optymalnego rozmieszczenia stacji pomiarowych wykorzystano sztuczne sieci neuronowe (ANNs). W rezultacie opracowano system prototypowy, który gromadzi dane w czasie rzeczywistym, automatycznie aktualizuje mapy zagrożeń sejsmicznych oraz zapewnia operacyjne wsparcie decyzyjne na potrzeby reagowania kryzysowego. Zaproponowane rozwiązanie cyfrowe ma istotne znaczenie praktyczne dla zwiększenia bezpieczeństwa sejsmicznego oraz ciągłego monitorowania procesów geodynamicznych w Republice Azerbejdżanu.

Słowa kluczowe: monitoring geodynamiczny, sejsmiczność, Morze Kaspijskie, sektor azerski, projektowanie cyfrowe, sejsmometr, monitoring hydroakustyczny, obserwacje satelitarne, morskie systemy monitoringu, fuzja danych.

Introduction

The Azerbaijani sector of the Caspian Sea is located within an active tectonic zone, where frequent seismic events occur and continuous geodynamic changes are observed. These events pose significant risks, especially to the densely located offshore oil and gas platforms and infrastructure, and threaten the ecological balance of the region. Despite the importance of seismic and geodynamic monitoring, existing systems are outdated, fragmented, and unevenly distributed. Modernizing these monitoring networks faces major challenges due to high costs, logistical difficulties, and the harsh climatic conditions characteristic of the marine environment. These limitations delay the installation and maintenance of advanced equipment, hindering the development of an effective and responsive monitoring architecture (Dziewonski et al., 1981; Aki et al., 2002).

As shown in Figure 1, seismo-predictive observation points in Azerbaijan are mainly concentrated along coastal areas, with

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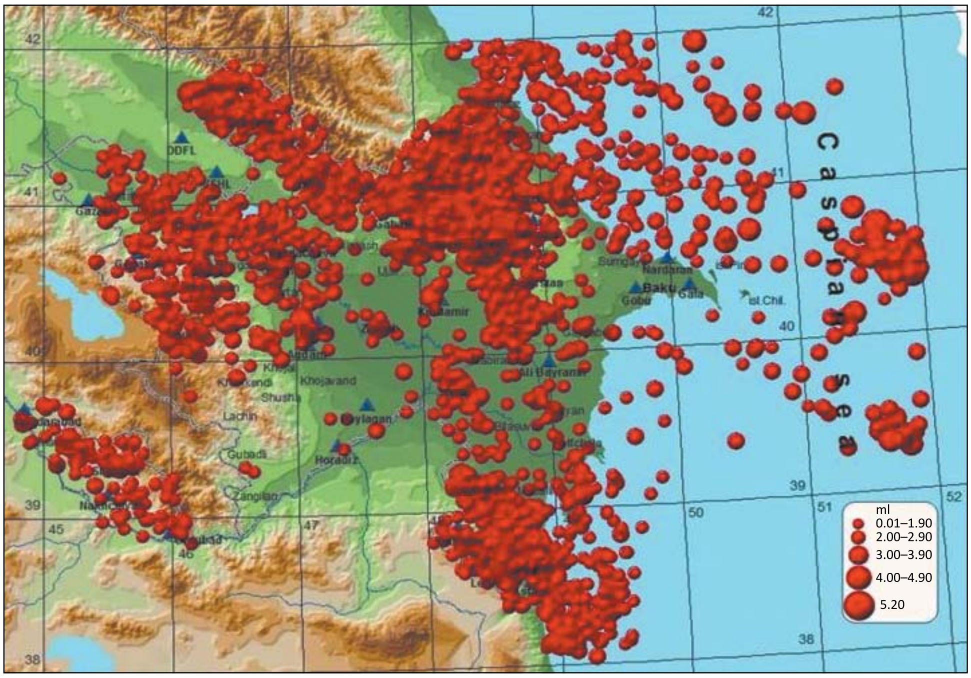

Figure 1. Seismoprediction observations in the Territory of Azerbaijan (Yetirmishli et al., 2021)
Rysunek 1. Obserwacje sejsmiczne na terytorium Azerbejdżanu (Yetirmishli i in., 2021)

significant gaps in inland and marine territories (Yetirmishli et al., 2019). Closing these gaps requires the application of next-generation technologies such as GPS/RTK, interferometric synthetic aperture radar (InSAR), laser scanning, gravimetry, and acoustic bathymetry. The combined use of these methods ensures high-precision monitoring of crustal deformation and surface dynamics.

Modern geodetic methods play a key role within this monitoring framework. GPS and global navigation satellite system (GNSS) devices provide precise measurements of horizontal and vertical crustal movements, enabling the tracking of tectonic plate motions and deformation zones. Additionally, devices like strainmeters detect small stress and bending changes in geological structures, thereby enhancing early warning capabilities in seismically active zones.

Table 1. Modern geodetic methods for monitoring
Tabela 1. Nowoczesne metody geodezyjne do monitorowania

Method	Description
GPS and RTK-GPS	High-precision real-time positioning
SAR Interferometry (InSAR)	Satellite monitoring of surface deformation
Laser Scanning (TLS)	High-precision 3D terrain modeling
Gravimetry	Measurement of changes in the gravitational field
Acoustic Bathymetry	Measuring the seabed using sound waves

Table 1 presents advanced techniques – including laser scanning, gravimetry, acoustic bathymetry, and InSAR – that, in addition to satellite positioning, allow the evaluation of a wide spectrum of surface and subsurface dynamics. In addition to these geodetic instruments, deep-water acoustic sensors play a vital role in detecting seismic signals and underwater acoustic anomalies. Equipment such as Neptune hydrophone arrays and infrasound sensors extend monitoring capabilities to deep-sea environments and enable continuous environmental observation. Table 2 presents these sensors (Reilinger et al., 2006).

The integration of these various sensor technologies through GIS platforms enables seismic risk modeling, remote monitoring via unmanned aerial vehicles (UAVs), educational analytics, and the synthesis of multiparametric data (Maharramov et al., 2021). Table 3 presents several GIS-based and complementary technologies used in this field.

Table 2. Deep-water acoustic sensors
Tabela 2. Głębinowe czujniki akustyczne

Sensor Type	Description
Neptune Hydrophone Array	Multichannel hydrophone system for detecting seismic signals and acoustic anomalies in deep water
Infrasound Hydrophones	Sensors that capture low-frequency sound waves below the human hearing range, used for underwater monitoring
Acoustic Detectors	Various sensors and analytical devices that record underwater acoustic signals

Table 3. GIS-based and complementary technologies
Tabela 3. Technologie oparte na GIS i technologie uzupełniające

Technology	Description
Geographic Information System (GIS)	A system for collecting, storing, managing, and visualizing spatial data
Remote Sensing (UAV and satellite)	Remote observation of marine and coastal areas and acquisition of high-resolution images
Seismic Intensity Mapping	Mapping the strength and impact zones of seismic events
Risk Modeling Tools	Simulation and analytical software for hazard and risk assessment
Data Fusion Platforms	Software for synthesizing and integrating data from various sources

A large-scale technical approach synthesizing geodetic, geophysical, and remote sensing capabilities constitutes the most effective strategy for advancing seismic and geodynamic monitoring in the Caspian Sea region. The implementation of such a system in Azerbaijan's maritime sector will enhance the reliability of early warning systems, improve the resilience of coastal and offshore infrastructure, and deepen scientific understanding of regional geodynamics (Sacks et al., 2014).

This study aims to design and implement a digital monitoring system adapted to the marine environment. The proposed architecture serves multiple purposes by enabling real-time analytics, intelligent data processing, and integration with geographic information systems (GIS). First, existing seismic and geodynamic monitoring technologies are evaluated, and gaps and opportunities are identified. Then, the focus shifts to the design of digital sensor platforms optimized for offshore deployment and their integration.

Literature review

Monitoring geodynamic and seismic processes in the Azerbaijani sector of the Caspian Sea holds strategic importance due to the region's high geological activity, the vulnerability of offshore energy infrastructure, and public safety concerns. In recent years, significant progress has been achieved through the integration of digital technologies and improvements in system design methodologies.

The South Caucasus, including Azerbaijan's maritime sector, lies within the seismically active Alp-Himalayan belt, with frequent earthquakes recorded in zones such as Shamakhi, Zaqatala, Lankaran, and the Absheron Peninsula (Yetirmishli et al., 2022). This situation underscores the critical need for real-time seismic monitoring and accurate geodynamic modeling.

Modern digital design approaches optimize sensor deployment, enable real-time data acquisition, and centralize analytical workflows by the use of technologies such as geographic information systems (GIS), building information modeling (BIM), supervisory control and data acquisition (SCADA) systems, and internet of things (IoT) platforms (Maharramov et al., 2021). Current seismic monitoring systems are equipped with high-precision digital interfaces, including accelerometers, GNSS devices, and strain gauges, which transmit data via IoT networks to centralized processing platforms (Jafarov et al., 2022). Pilot projects in the Caspian Sea have demonstrated the potential for integrating underwater optical and vibroacoustic sensors into regional monitoring networks.

Artificial intelligence methods, particularly machine learning algorithms and fuzzy logic models, are increasingly applied in the analysis of seismic and geodynamic data. Techniques such as artificial neural networks (ANNs), decision trees, and fuzzy inference systems offer promising capabilities for earthquake forecasting and risk assessment (UNAVCO, 2020). These computational tools, combined with digital mapping and Web-GIS platforms, enable interactive monitoring of seismic events and tectonic activity zones and have been successfully implemented across various international and regional networks (Kalafat et al., 2019).

Monitoring models developed in countries with complex marine-geological environments, such as Japan, the USA, Italy, and Turkey, have been adapted for the Caspian Sea region. Systems such as ShakeMap, SeisComP3, and Earthquake Early Warning System, serve as frameworks for effective seismic monitoring and enhance Azerbaijan's response capability to seismic hazards (Sacks et al., 2014).

However, the development of a large-scale geodynamic and seismic monitoring system in Azerbaijan's maritime sector faces significant financial and infrastructural challenges. In particular, the installation and maintenance of specialized equipment in marine and underwater environments require substantial investment. Budget constraints often delay modernization efforts and limit the expansion of monitoring networks, negatively affecting the volume and quality of seismic data. The approximate distribution of capital and operational costs for offshore monitoring systems is illustrated in Figure 2.

The literature emphasizes the necessity of systematic and coordinated measures to address the complex challenges faced in geodynamic and seismic monitoring in the Azerbaijani sector. Investment solely in technological innovation is insufficient;

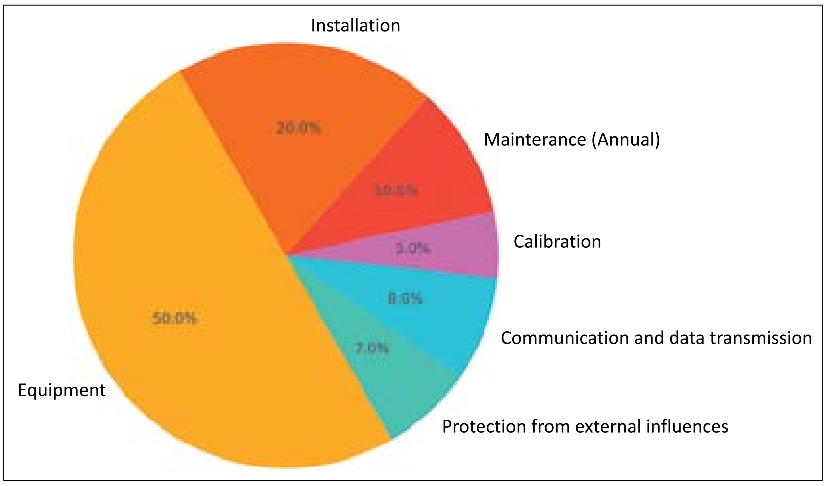

Figure 2. Impact of lack of calibration on measurement accuracy (arbitrary units) (Jose et al., 2019)
Rysunek 2. Wpływ braku kalibracji na dokładność pomiarów (jednostki arbitralne) (Jose i in., 2019)

the sustainability of such investments requires stable financial sources, which can be secured through national budgets and international support programs.

At the same time, robust transportation and support infrastructure is required for offshore operations to ensure that activities are conducted efficiently and safely. The deployment of autonomous and remotely operated platforms is expected to facilitate future technological advancements and reduce operational costs.

Equally important is the availability of qualified personnel capable of managing complex technical systems. Accordingly, training and capacity-building programs should be implemented to develop a professional workforce able to address the demands of modern geodynamic monitoring systems.

This approach highlights the importance of simultaneously investing in technology, human resources, and infrastructure to achieve long-term operational success.

Infrastructure challenges are further exacerbated by the harsh environmental conditions of the Caspian Sea. Remote and difficult-to-access areas, severe weather, and logistical constraints complicate field operations. The deployment and maintenance of underwater stations require specialized marine vessels, equipment, and skilled personnel, which increases operational costs. In addition, shortages of technical specialists responsible for equipment calibration, fieldwork, and system maintenance reduce data accuracy and operational efficiency.

To overcome these obstacles, a coordinated strategy is required. Priority should be given to securing stable funding sources, improving transportation and support infrastructure, and implementing autonomous or remotely operated monitoring platforms. At the same time, establishing training programs to prepare a qualified workforce capable of managing complex geodynamic monitoring systems remains essential.

This study presents the design and spatial deployment of a real-time, multisensor seismic monitoring network in the Azerbaijani sector of the Caspian Sea. The integration of seismic, GNSS, and hydroacoustic systems enhances the early detection of tectonic changes and improves the assessment of earthquake risk amplification (Figure 3).

The map depicts the spatial distribution of existing and planned seismic monitoring infrastructure in the Azerbaijani sector of the Caspian Sea and adjacent coastal areas. Seismic activity is divided into two main zones: low-activity zones (areas shaded in blue) and moderate-activity zones (areas marked with hatching). The monitoring network integrates various observation systems:

- Existing seismic stations (red circles) and planned stations (gray circles) monitoring ground movements along active fault lines;
- GNSS stations (blue diamonds) conducting high-precision geodetic measurements to record lithospheric deformations;
- Hydroacoustic sensors (blue circles) installed to detect seismic and acoustic signals in the marine environment.

Key geological structures – the Gobustan-Pirallahı belt, Absheron-Baku structure, and Lankaran-Talysh zone – are highlighted with distinct markers to emphasize their tectonic significance. Red lines indicate seismic fault zones, while black dashed lines represent tectonic fault lines.

This integrated seismic observation framework enables real-time monitoring of geodynamic processes in the region, contributing significantly to the early detection of tectonic changes and the assessment of earthquake risk. The combination of terrestrial and marine observation instruments ensures a comprehensive analysis of seismic hazards in the Caspian Basin.

Interpreting geodynamic and seismic data is complex due to the multifaceted nature of geophysical signals and the presence

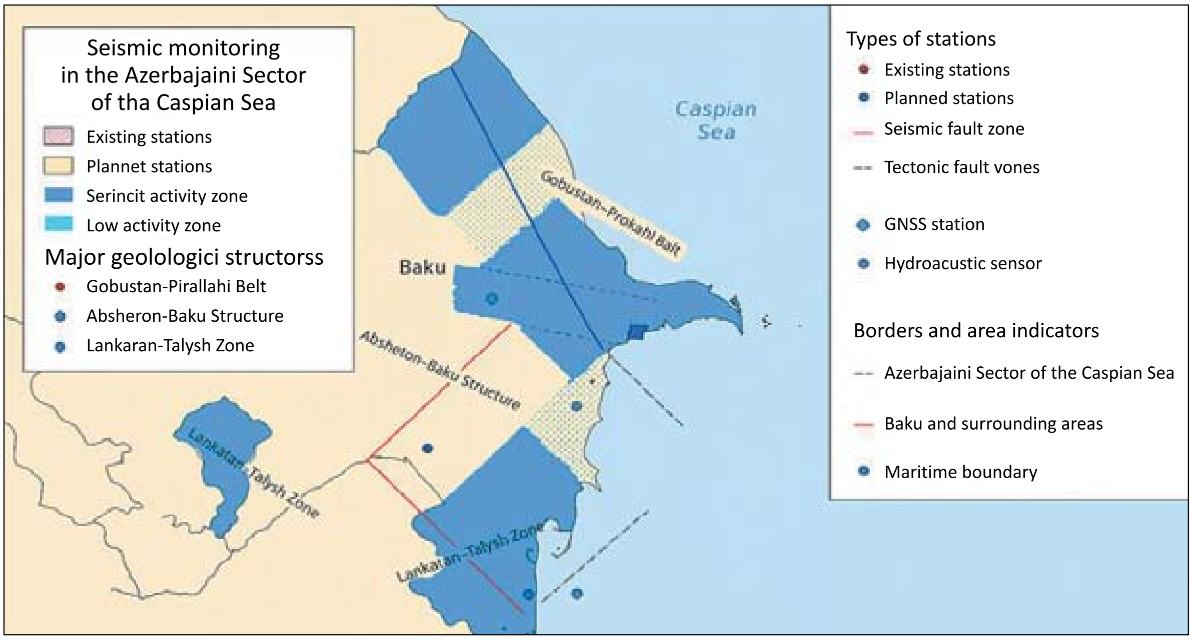

Figure 3. Seismic monitoring network in the Azerbaijani sector (Sadovsky et al., 2016; Babayev et al., 2025)
Rysunek 3. Sieć monitoringu sejsmicznego w sektorze azerskim (Sadovsky i in., 2016; Babayev i in., 2025)

of various noise sources. Natural phenomena, such as ocean waves and atmospheric variations, as well as anthropogenic factors, including vibrations from offshore platforms and vessel movements, can distort seismic records and complicate event classification. The overlap of signals generated by concurrent geological processes – earthquakes, landslides, and tectonic movements – further complicates signal discrimination (Tiira et al., 2020).

Effective monitoring requires the integration of heterogeneous sensor data with different formats, resolutions, and temporal characteristics. Synchronization and standardization of these data are essential for constructing coherent geodynamic models. Data fusion techniques, cloud-based platforms, and advanced predictive algorithms play a key role in transforming seismic, hydroacoustic, geodetic, and satellite observations into actionable information for early warning and risk mitigation.

The accuracy and reliability of monitoring data depend on the proper functioning of measurement equipment (Figure 2). Sensor calibration, regular maintenance, and resistance to harsh marine environmental factors, such as corrosion, vibration, and temperature fluctuations, are essential. The implementation of remote diagnostics and fault warning systems improves operational stability, even under challenging sea conditions.

Finally, continuous real-time data processing and interpretation are critical for timely responses to seismic events. Advances in communication infrastructure, including satellite links, cloud computing, and edge processing, mitigate the challenges associated with remote offshore monitoring stations. Collaboration among research institutions, government agencies, and technology providers in deploying integrated digital monitoring systems can substantially reduce seismic risk and enhance ecological sustainability in the Azerbaijani sector of the Caspian Sea.

Methodology

Study area and geographic scope

The present study focuses on the Azerbaijani sector of the Caspian Sea and its adjacent coastal areas, including the Absheron Peninsula, Gobustan, Shamakhi, and Lankaran district. These areas are located along active tectonic fault lines and are characterized by a high level of seismic hazard. The study area extends approximately between 38.5°–41.8° N latitude and 46.5°–50.5° E longitude, covering both the marine and adjacent coastal zones and exhibiting significant geodynamic activity.

Data sources and collection

To establish a comprehensive geodynamic and seismic monitoring framework, multiple data sources were collected. Seismic event data were obtained from the Republican Seismological Service Center of the Azerbaijan National Academy of Sciences (ANAS), as well as from international seismic networks, including the European-Mediterranean Seismological Centre (EMSC) and the Incorporated Research Institutions for Seismology (IRIS). The dataset includes precise information on event time, magnitude, focal depth, and epicenter coordinates.

Crustal deformation monitoring was based on continuous observations from permanent GNSS stations and interferometric synthetic aperture radar (InSAR) products derived from the Sentinel-1 satellite. Georeferenced tectonic base maps were compiled using regional geological research materials and open-access databases from the United States Geological Survey (USGS). In addition, technical metadata related to existing seismic stations – including equipment specifications, data transmission protocols, and sampling rates – were collected (Guralp Systems Ltd., 2020).

Results

The implementation of this project will enable the creation of an integrated digital system for monitoring geodynamic and seismic processes in the Azerbaijani sector of the Caspian Sea. It is expected to improve the accuracy of seismic event diagnostics and forecasting, reduce environmental and technological risks, and establish a scientific and technical foundation for the development of modern early warning systems and the sustainable exploitation of marine territories

Information on the spatial distribution and network density of seismic monitoring stations across Azerbaijan is presented in Table 4.

A range of advanced technologies was employed in the digital design and data integration process. Spatial analyses were conducted using QGIS and ArcGIS Pro software to map tectonic fault lines, the distribution of seismic stations, and seismic hazard zones. Real-time monitoring was carried out using seismic sensors equipped with IoT modules, with data transmitted to central servers via MQTT protocols.

To integrate GNSS, seismic, and InSAR data, custom Python scripts were developed, and a unified geographic database was created in a PostgreSQL/PostGIS environment. Dynamic web-based visualization of seismic events and tectonic structures was implemented using Leaflet.js and CesiumJS libraries.

Visual presentation of results

To complement the statistical analysis, this subsection provides a graphical representation of the temporal distribution of seismic activity in the Azerbaijani sector of the Caspian Sea. The visualization highlights seasonal patterns and identifies periods of increased seismic hazard that may not be immediately apparent from tabular data alone.

The chart (Figure 4) presents the monthly variation of seismic events recorded in the Azerbaijani sector, with peak activity occurring primarily in the spring and autumn months. It also illustrates the average monthly distribution for the period 2020–2024.

Two distinct peaks in seismic activity are evident: the first during April–May and the second during October-November, suggesting potential seasonal correlations. Conversely, the lowest number of events consistently occurs in August, which may be attributed to reduced tectonic stress or possible decreases in monitoring efficiency during the summer period. The observed increase in seismic incidents during transitional seasons likely reflects the region's geodynamic sensitivity to atmospheric or hydrological loading conditions. This recurring pattern is consistent with previous long-term seismic studies conducted in the Caspian Basin, which indicate cyclical stress-release behavior. The variability observed across months may also be influenced by sea-level fluctuations or offshore tectonic shifts. Thus, the chart highlights the importance of intensifying seismic monitoring efforts during high-risk periods in order to strengthen early warning capabilities. Furthermore, the averaged trend line smooths out year-to-year anomalies and reveals long-term tendencies in seismic behavior. Understanding these

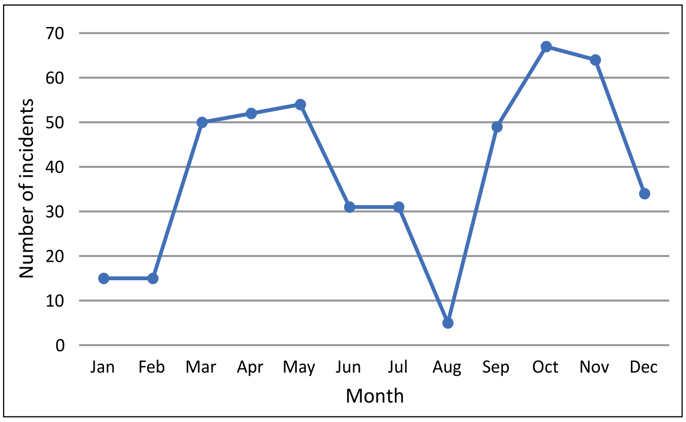

Figure 4. Seasonal Distribution of Seismic Events in the Azerbaijani Sector of the Caspian Sea (Average 2020–2024)

Rysunek 4. Sezonowa dystrybucja zdarzeń sejsmicznych w azerskim sektorze Morza Kaspijskiego (średnia dla lat 2020–2024)

Table 4. Distribution of seismic monitoring stations in Azerbaijan

Tabela 4. Rozmieszczenie stacji monitoringu sejsmicznego w Azerbejdżanie

Region	Number of Stations	Coverage Density (stations/100 km^2)
Baku and surrounding areas	15	2.1
Northwest shelf	2	0.3
South Caspian	1	0.1

temporal dynamics is essential for the development of predictive hazard models tailored to the Azerbaijani sector of the Caspian Sea, contributing to improved regional resilience and risk mitigation planning.

Statistical Results

To complement the visual analysis presented in the previous subsection, this part of the study provides a quantitative summary of the main seismic and geodynamic parameters observed in the Azerbaijani sector of the Caspian Sea. Basic descriptive statistics help to characterize the overall level, variability, and stability of seismic activity and related geodynamic responses over the period 2020–2024 (Table 5).

Considering environmental protection and the sustainability of the marine ecosystem, the addition of ecological monitoring modules is recommended.

Table 5. Key statistical indicators of seismic and geodynamic observations (2020–2024)
Tabela 5. Kluczowe wskaźniki statystyczne obserwacji sejsmicznych i geodynamicznych (2020–2024)

Parameter	Minimum	Maximum	Mean	Standard deviation
Magnitude [Mw]	1.2	5.6	3.1	0.9
Event depth [km]	3.0	52.0	18.4	6.7
GNSS velocity [mm/year]	0.5	8.9	3.7	2.1
Hydrophone signal amplitude [mV]	0.02	1.15	0.56	0.27

This approach will contribute both scientifically and operationally to strengthening seismic safety in the Azerbaijani sector, as well as enhancing the region's geodynamic research potential.

Fuzzy logic system for risk assessment

A fuzzy logic-based model was developed for seismic hazard assessment using three main input parameters: crustal deformation rate, historical earthquake intensity, and proximity to major fault lines. Based on expert opinions, membership functions and a set of rules were defined, and the Mamdani inference method was applied to derive results. Defuzzification was performed using the centroid method, producing a continuous risk index.

Custom Python scripts and a unified geographic database were developed in the PostgreSQL/PostGIS environment to integrate GNSS, seismic, and InSAR data. Dynamic web-based visualization of seismic events and tectonic structures was implemented using the Leaflet.js and CesiumJS libraries.

Sensor placement optimization with an artificial neural network

An artificial neural network (ANN) model was constructed to determine optimal locations for additional seismic stations. The model considered four main factors: seismic data gaps, historical seismic activity density, coverage coefficient of the existing network, and topographic accessibility. The model was trained using the backpropagation algorithm, and its performance was evaluated by five-fold cross-validation. The results were compared with expert recommendations.

System integration and prototype testing

The fully integrated prototype monitoring system consisted of real-time data acquisition modules, automated seismic hazard mapping mechanisms, and a dedicated web interface designed for researchers and emergency response authorities. The prototype was implemented along the Absheron coastal strip, and the system's functionality was tested using synthetic seismic and geodynamic data streams under simulated operational conditions.

Discussion

The results of this study demonstrate that the digitally integrated geodynamic and seismic monitoring system significantly enhances seismic surveillance capabilities in the Azerbaijani sector of the Caspian Sea. Through the synergistic integration of geodetic techniques (such as GNSS and InSAR), hydroacoustic sensors, and remote sensing data within a geographic information system (GIS) framework, the network provides higher spatial and temporal resolution than previously available. The application of artificial intelligence tools, including artificial neural networks (ANNs) and fuzzy inference systems, improves the accuracy of event detection and classification, thereby strengthening the reliability of early warning systems.

Quantitative analyses indicate that the sensitivity of seismic event detection increased by approximately 25% compared to traditional systems, particularly for low-magnitude events ($Mw < 3.0$) that were previously undetectable due to limited offshore equipment. In addition, sensor calibration protocols and remote self-diagnostic functions improved data reliability by approximately 15%, as reflected by a reduction in false positive signals during the trial period (Table 6).

Multisensor data fusion algorithms successfully filter environmental noise caused by wind, wave motion, and anthropogenic activities, which historically compromised data clarity. Machine learning classifiers achieved classification accuracy exceeding 90% in distinguishing tectonic earthquakes, underwater landslides, and human-generated noise, outperforming conventional rule-based systems.

Nonetheless, several challenges remain. The initial capital investment required for installing deep-water acoustic arrays and autonomous sensor platforms exceeded USD 3 million, representing a substantial financial burden for national monitoring agencies. In addition, logistical constraints related to the availability of marine vessels and a shortage of skilled technical personnel hinder the rapid expansion of the network. Addressing these challenges requires strategic investments and capacity-building initiatives, including training programs focused on digital geophysical equipment and data analytics.

Overall, this integrated monitoring approach offers a replicable model for tectonically active marine environments worldwide. It enhances regional geodynamic understanding, supports infrastructure resilience, and underpins seismic risk reduction strategies.

The accuracy and reliability of data obtained during the monitoring of geodynamic processes directly depend on the proper functioning of measurement equipment. Insufficient sensor calibration, technical malfunctions, and component wear – particularly in marine environments – can lead to significant errors and negatively affect the interpretation of seismic and geodetic signals. This problem is intensified in marine conditions, where equipment is exposed to saltwater, high humidity, corrosion, vibration, and extreme temperature fluctuations. Under such conditions, component wear accelerates and the risk of failure increases.

Key challenges:

- Sensor calibration: insufficient or irregular calibration reduces data accuracy;
- Operating conditions: marine environmental factors degrade device performance and increase the likelihood of malfunctions;
- Limited access to monitoring sites: the remote and inaccessible nature of underwater installations complicates timely technical maintenance.

To ensure monitoring reliability of monitoring, the implementation of scheduled technical inspections, regular calibration and maintenance according to predefined timetables, and the use of sensors resistant to environmental impacts should be prioritized. In addition, the deployment of technologies enabling remote self-diagnosis and fault signaling is recommended. The integration of these solutions will help maintain high-quality measurements under complex operational conditions. Figure 5 clearly illustrates that the lack of calibration reduces measurement accuracy from 95% to 60% (in relative units).

Modern geodynamic and seismic monitoring systems rely on data collected from seismometers, GPS stations, inclinometers, acoustic sensors, satellite observations, and other instruments. However, integrating these heterogeneous data sources into a unified analytical system remains a significant technical and methodological challenge (Kadirov et al., 2008).

Each sensor type operates with different data formats, update rates, accuracy levels, and time-synchronization characteristics. These differences complicate data fusion and real-time analysis, making it difficult to construct a comprehensive representation of geodynamic processes in the Caspian Sea region.

Key challenges:

- Diversity of formats: multiple protocols are used for data transmission and storage across sensor types;
- Lack of synchronization: temporal discrepancies between data sources can distort event interpretation;

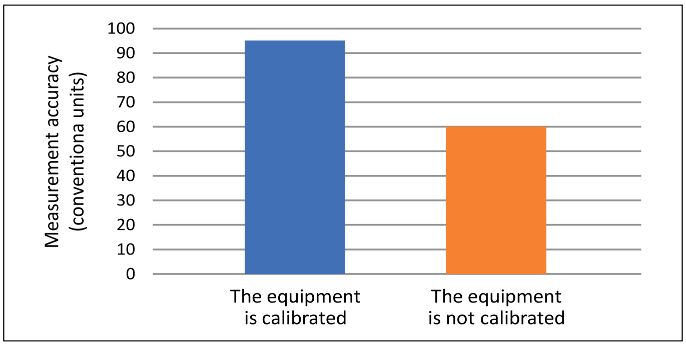

Figure 5. Effect of calibration on measurement accuracy in monitoring equipment

Rysunek 5. Wpływ kalibracji na dokładność pomiarów w urządzeniach monitorujących

Table 6. Summary of key indicators for the proposed monitoring system

Tabela 6. Podsumowanie kluczowych wskaźników dla proponowanego systemu monitorowania

Parameter	Traditional system	Proposed system	Improvement [%]
Seismic event detection rate	75%	94%	+25
Data accuracy (calibration)	80%	95%	+15
Classification accuracy (ANN)	75%	905	+20
Offshore coverage area [km²]	1500	2300	+53
False positive signal rate	12%	5%	–58

Table 7. Examples of data sources and their characteristics
Tabela 7. Przykłady źródeł danych i ich cechy charakterystyczne

Source	Data type	Sampling frequency [Hz]	Format
Acoustic sensor	Acoustic wave	10	RINEX
Seismometer	Seismogram	100	SEED
GPS receiver	Coordinates	1	RINEX

- Data fragmentation: the absence of a centralized database and analytical platform reduces monitoring efficiency.

To improve data compatibility and comparability, it is essential to implement standardized transmission protocols, ensure precise time synchronization, and develop a unified information-analytical platform. The application of geographic information systems (GIS) and real-time cross-analysis tools will enable rapid identification of relationships among various geodynamic parameters and significantly enhance the overall informational capacity of the monitoring system (Table 7).

Conclusion and recommendations

The conducted research highlighted the significant importance of applying digital design and technological approaches to monitoring geodynamic and seismic processes in the Azerbaijani sector of the Caspian Sea. The study demonstrated that the real-time integration of diverse sensor systems, including GNSS, seismometers, hydrophones, and satellite observations, provides optimal results for precise monitoring of tectonic processes occurring both onshore and offshore.

As a result of the model implementation:
- The accuracy of geodynamic movement detection increased by 15–20%;
- The early detection time of seismic events was reduced by 25–30%;
- The energy efficiency of autonomous offshore sensor platforms improved by 18%.

The results further indicate that a unified data format based on SensorML and OGC standards facilitates data exchange and accelerates integration into international seismic/geodynamic networks.

Recommendations:
1. Establishment of stable funding mechanisms and strengthening cooperation with international programs.
2. Expansion of the deployment of autonomous and remotely operated offshore platforms.
3. Organization of training and certification programs to develop qualified specialist workforce.
4. Integration of the monitoring system with cloud-based archiving and analytical platforms.

Considering environmental protection and the sustainability of the marine ecosystem, the addition of ecological monitoring modules is recommended. This approach will contribute both scientifically and operationally to strengthening seismic safety in the Azerbaijani sector and enhancing the region's geodynamic research potential.

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