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DEVELOPMENT OF AN ENVIRONMENTAL MONITORING INFORMATION SYSTEM ON THE COAST OF THE NORTHERN PART OF THE CASPIAN SEA

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Abstract. This paper presents a comprehensive study on designing and implementing an Environmental Monitoring Information System (EMIS) tailored for the northern coast of the Caspian Sea. The system integrates in situ sensor networks, satellite remote sensing, and predictive analytics to track critical ecological parameters such as water quality, biodiversity, and hydrocarbon pollution. A modular architecture ensures flexibility and scalability, facilitating real-time data acquisition and processing. The project addresses unique environmental challenges in this region, including fluctuating sea levels, anthropogenic impacts from oil extraction, and climate-induced habitat changes. By providing stakeholders—government agencies, industry operators, and local communities—with continuous data streams and visual analytics, the EMIS supports timely decision-making and sustainable resource management. The paper highlights key technical considerations, from sensor calibration to data storage solutions, and offers case studies demonstrating how the system helps detect anomalies, forecast risks, and preserve ecosystem health along the northern part of the Caspian Sea.

Keywords. Environmental Monitoring Information System, Northern Caspian Sea, sensors and Sensor Networks, remote Sensing, Data Analysis (Big Data), Predictive Models, Sustainable Resource Management, Water Quality and Pollution.

Introduction

The Caspian Sea, the world's largest inland body of water, spans multiple countries and features highly diverse ecosystems. In its northern part, rich biodiversity coexists with intensive industrial activities such as oil and gas extraction, fisheries, and maritime shipping. The region's fragile balance faces increasing anthropogenic and climate stressors, including sea-level fluctuations, contamination by hydrocarbons, eutrophication, and habitat loss. These challenges underscore the importance of effective environmental monitoring.

An Environmental Monitoring Information System (EMIS) is vital for collecting, processing, and interpreting ecological data. Such systems provide real-time information that can inform policy decisions, guide industry best practices, and engage local communities in conservation. Although prior studies have explored discrete monitoring components—like remote sensing or sensor networks—few have integrated these into a cohesive, scalable, and user-focused architecture. Our paper aims to bridge this gap by detailing the design, development, and validation of an EMIS optimized for the northern Caspian coastline.

The absence of a robust, unified monitoring framework has led to fragmented datasets, delayed responses to ecological threats, and uneven data accessibility among stakeholders. Traditional monitoring often relies on sporadic sampling campaigns, manual measurements, or data stored in isolated databases. Such limitations hamper regional environmental management. Hence, there is a critical need for a comprehensive system capable of automatically collecting data from diverse sources—field sensors, satellites, meteorological stations—and processing them in near real time. This system should also present actionable insights via a user-friendly dashboard to facilitate timely decision-making.

1. Design a Modular Architecture

Create a flexible system that can integrate heterogeneous data sources, accommodate future sensor expansions, and adapt to the evolving needs of stakeholders.

2. Incorporate Advanced Data Analytics

Implement machine learning models for anomaly detection, pattern recognition, and predictive forecasting of water quality and ecological risks.

3. Develop Visual Analytics Dashboards

Provide stakeholders with accessible, real-time insights to guide sustainable resource management and regulatory compliance.

4. Validate the System

Conduct pilot tests and case studies to ensure reliability, accuracy, and user acceptance of the proposed EMIS.

The system is designed primarily for the northern coastline of the Caspian Sea. While many components can be generalized for the entire Caspian region, certain modules (e.g., tide prediction or specific pollution pathways) may require region-specific calibrations. Furthermore, although the EMIS emphasizes real-time data, its operational efficiency depends on infrastructure reliability, continuous sensor maintenance, and stable funding. The study does not delve deeply into the socio-economic or political aspects of environmental management, focusing instead on the technical framework necessary for effective monitoring.

Literature review

Environmental Monitoring Frameworks

Various approaches to environmental monitoring have been proposed globally, many focusing on sensor-based or satellite-based solutions [1]. While these studies highlight the importance of integrated systems, relatively few address the ecological nuances of the Caspian Sea, where salinity gradients, seasonal freezing, and unique biodiversity patterns demand specialized solutions.

Remote Sensing Techniques

Satellite imagery and unmanned aerial vehicles have proven effective for large-scale monitoring of water quality parameters such as chlorophyll-a concentration, temperature anomalies, and algal blooms [2]. Synthetic Aperture Radar (SAR) data, for instance, have been employed to detect oil spills. However, satellite data often lack the temporal resolution for real-time interventions, underscoring the need for in situ sensors that can fill observation gaps [3].

Sensor Networks

Sensor networks deployed in marine environments track parameters like temperature, turbidity, dissolved oxygen, pH, and pollutant concentrations. Low-power, wide-area networks (LPWANs) offer potential for real-time data transmission with minimal energy consumption [4]. Nonetheless, sensor fouling, corrosion, and the challenge of powering remote nodes remain significant bottlenecks.

Big Data and Machine Learning Applications

Machine learning algorithms—particularly deep learning models—have gained traction in ecological applications, including species distribution modeling, pollution forecasting, and anomaly detection in water quality signals [5]. Cloud-based platforms can handle massive datasets, enabling continuous training of predictive models. The reliability of these models depends heavily on data quality and domain expertise for feature engineering [6].

Gaps in Existing Research

Few studies provide end-to-end solutions that unify remote sensing, sensor networks, and advanced analytics into a single platform for the Caspian Sea. Additionally, efforts to tailor user-facing dashboards for local stakeholders—considering linguistic, cultural, and regulatory requirements—are limited. Our proposed EMIS aims to address these deficiencies by offering a holistic, region-specific approach.

Methodology

Overall Research Design

Our methodology combines a systems engineering approach with extensive field validation. The research design involves:

1. *Requirements Analysis*: Engaging local agencies, research institutions, and industry operators to define system specifications.

2. *System Architecture Development*: Designing modular components for data acquisition, processing, and visualization.

3. *Implementation*: Coding and deploying the system on cloud-based servers with failover and redundancy.

4. *Field Testing*: Pilot deployment in selected northern Caspian coastal areas.

5. *Evaluation*: Assessing system performance, accuracy, and user satisfaction; refining the architecture as necessary.

Study Area

The northern Caspian Sea exhibits shallow depths, significant seasonal ice coverage, and extensive coastal wetlands. Major urban centers and industrial facilities cluster near the coast, affecting local water quality. Seasonal fluctuations lead to complex hydrodynamics, further complicating data interpretation. Figure 1 (ASCII-based schematic map below) highlights the approximate coastline and pilot sites.

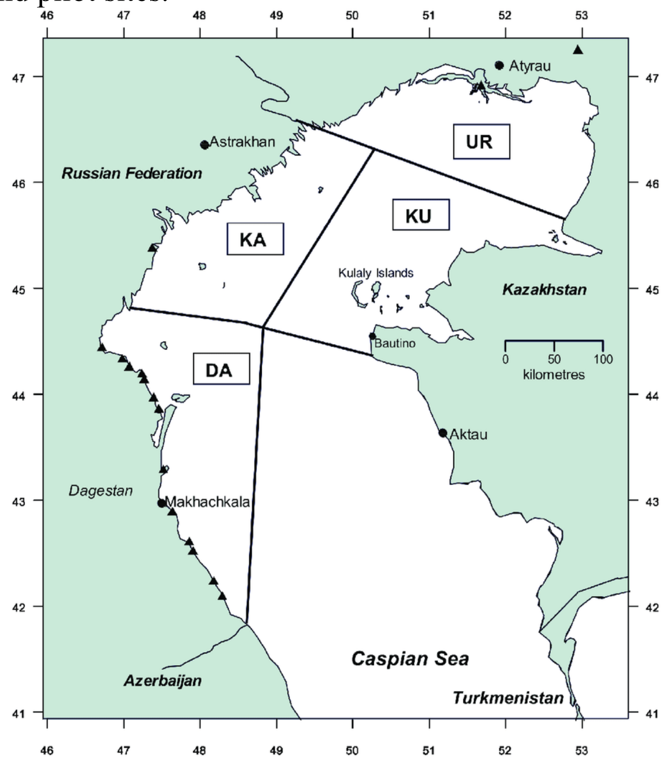

Figure 1. Schematic map of the Northern Caspian Sea region with pilot study locations.

<u>Sensor Network Configuration</u>

Sensors measuring temperature, salinity, pH, turbidity, dissolved oxygen, and hydrocarbon concentrations are strategically positioned along the coastline and near industrial outfalls. Each sensor node features:

- *Data Logging*: Local data storage and buffer in case of network disruptions.
- *Power Management*: Solar panels plus battery backup to ensure continuous operation.
- *Wireless Connectivity*: LPWAN modules (e.g., LoRaWAN) for long-range, low-power communication.

Table 1. Key Sensor Types and Specifications

Parameter	**Sensor Model**	**Range**	**Accuracy**	**Communication**
Temperature	TX-200 Marine Probe	-5°C to 40°C	±0.1°C	LoRa
Salinity	Salino-Sense CX	0–50 PSU	±0.2 PSU	LoRa

pH	AquaLogix pH-10	0–14	±0.02 pH	LoRa
Dissolved Oxygen	DOProbe Ultra	0–20 mg/L	±0.1 mg/L	LoRa
Hydrocarbon (Oil)	PetroDetect 3000	0–100 ppm	±1 ppm	LoRa

Remote Sensing and Data Fusion

Satellite imagery from Sentinel-2 and Landsat 8 is automatically downloaded at scheduled intervals. Remote sensing data on sea surface temperature, turbidity, and chlorophyll-a are fused with in situ measurements via a Kalman filtering approach. This fusion compensates for missing or noisy sensor data and enhances spatial coverage.

Data Processing

A central cloud server ingests raw sensor data through secure MQTT or HTTP protocols. Pre-processing pipelines handle data validation (outlier detection, interpolation), metadata tagging (timestamp, geolocation), and transformations (unit normalization). The system's data lake stores both raw and processed data for historical analyses, while a real-time analytics module supports immediate anomaly detection.

Predictive Modeling

Machine learning models (Random Forest, LSTM networks) are employed to forecast short-term changes in water quality parameters. For example, a predictive model might estimate the risk of an algal bloom based on rising water temperatures, historical patterns, and nutrient levels. The pipeline automatically retrains models as new data accumulate to enhance predictive accuracy.

User Interface and Visualization

A web-based dashboard, accessible via desktop and mobile browsers, provides role-based access. Stakeholders such as government officials, industry managers, and researchers can visualize data in interactive charts, heatmaps, or time-lapse animations. The interface includes alert mechanisms (SMS or email) triggered by threshold violations—e.g., high hydrocarbon levels or abrupt pH changes.

Layered Model

The proposed EMIS architecture is divided into three layers: **Data Acquisition**, **Data Processing**, and **Presentation**.

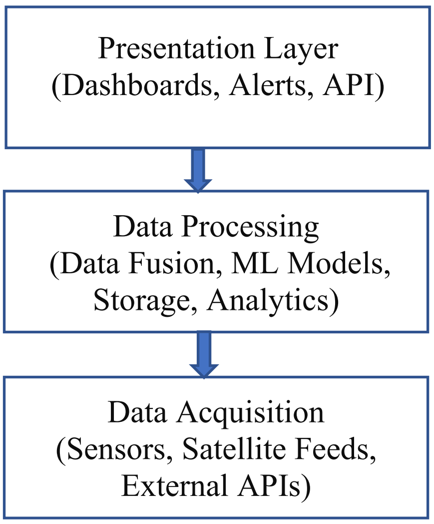

Figure 2. Layered Architecture of the EMIS

Communication Protocols

• **LoRaWAN**: Sensor node to gateway transmission due to its low power requirement and wide coverage.

- **4G/5G**: Gateway to the cloud for real-time backhaul, ensuring data rates are sufficient for large file transfers (e.g., satellite images).
- **MQTT**: Lightweight messaging protocol used for push-based sensor updates.
- **HTTPS**: Secured data transfer for system administration, data viewing, and analytics queries.

Security Considerations

End-to-end encryption (using TLS/SSL) protects sensor data in transit, while role-based authentication controls restrict dashboard functionality. Audit trails log all system interactions, ensuring accountability. Regular security patches and intrusion detection systems mitigate potential cyber threats.

Results

Pilot Deployment

We deployed a pilot EMIS in two locations (Pilot Site A and Pilot Site B). Each location included five sensor nodes measuring temperature, salinity, pH, and dissolved oxygen at 30-minute intervals, plus one specialized oil sensor at known industrial discharge points. Satellite data from Sentinel-2 were integrated daily. The pilot ran for six months under varied weather and sea conditions.

Data Quality and Reliability

The initial analysis showed data capture rates of over 95%. Sensor drift was minimal, with the DO and pH probes requiring monthly calibrations. Intermittent communication dropouts occurred due to inclement weather, which were effectively managed by local buffering and resumed transmissions once connectivity stabilized.

Detection of Anomalies

Using a Random Forest-based anomaly detection model, we identified three notable events of elevated hydrocarbon levels near Pilot Site B, correlating with scheduled industrial discharges. Additionally, an unusual drop in dissolved oxygen was detected near Pilot Site A, later confirmed to coincide with an algal bloom event. This near-real-time detection enabled a rapid response from local environmental agencies.

Stakeholder Feedback

A user survey revealed high satisfaction levels regarding the dashboard's clarity, with 85% of respondents stating the visualizations aided in quick decision-making. However, some local users advocated for a bilingual interface (English and Russian), and further expansions are planned to incorporate Kazakh.

Discussion

Technical Performance

The pilot demonstrated the feasibility of real-time ecological monitoring in the northern Caspian. A key technical strength lies in the system's modular design. By separating data acquisition, processing, and presentation layers, the architecture can scale or adapt to new sensor types without system-wide overhauls. The data fusion techniques, particularly the Kalman filter, effectively bridged temporal gaps in satellite imagery, enhancing overall data continuity.

Environmental and Regulatory Implications

A holistic monitoring system offers substantial benefits for regulatory compliance, especially in regions with active hydrocarbon extraction. Timely detection of pollutant discharges can prompt rapid remediation, reducing harm to local ecosystems. Moreover, reliable data serve as a basis for stricter emission controls and more sustainable resource usage, aligning with national and international environmental standards.

Socioeconomic Benefits

Accurate ecological data can foster sustainable fisheries, tourism, and coastal development. By reducing uncertainties, the system may attract environmentally conscious investments. Publicly accessible dashboards can also promote community engagement, encouraging citizen science initiatives and fostering a collective responsibility for environmental stewardship.

Challenges and Limitations

Despite the pilot's success, scaling up demands significant capital for sensor procurement, maintenance, and network infrastructure. Harsh winter conditions could increase sensor wear and energy demands. Data privacy and security concerns require robust enforcement of access controls. Finally, ensuring local ownership of the system—through capacity-building programs—remains pivotal.

Conclusions. This study details the design, implementation, and pilot testing of an Environmental Monitoring Information System tailored to the unique conditions of the northern Caspian Sea. Our EMIS integrates sensor networks, satellite remote sensing, and machine learning to deliver near-real-time insights into water quality and ecological health. Pilot results demonstrate strong potential for improving regulatory compliance, protecting marine biodiversity, and enabling data-driven policy decisions. Future expansions might include additional sensor parameters (e.g., heavy metal concentrations), advanced AI algorithms for predictive modeling, and localized user interfaces that cater to various language preferences. Overall, a scalable, flexible, and user-centric EMIS can serve as a cornerstone for sustainable marine resource management in the Caspian region.

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РАЗВИТИЕ ИНФОРМАЦИОННОЙ СИСТЕМЫ МОНИТОРИНГА ОКРУЖАЮЩЕЙ СРЕДЫ НА ПОБЕРЕЖЬЕ СЕВЕРНОЙ ЧАСТИ КАСПИЙСКОГО МОРЯ

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Аннотация. В данной статье представлено комплексное исследование по проектированию и внедрению информационной системы мониторинга окружающей среды (EMIS), адаптированной для северного побережья Каспийского моря. Система объединяет сенсорные сети in situ, спутниковое дистанционное зондирование и прогнозную аналитику для отслеживания критических экологических параметров, таких как качество воды, биоразнообразие и загрязнение углеводородами. Модульная архитектура обеспечивает гибкость и масштабируемость, облегчая сбор и обработку данных в реальном времени. Проект решает уникальные экологические проблемы в этом регионе, включая колебания уровня моря, антропогенное воздействие от добычи нефти и изменения среды обитания, вызванные климатом. Предоставляя заинтересованным сторонам — государственным учреждениям, операторам отрасли и местным сообществам — непрерывные потоки данных и визуальную аналитику, EMIS поддерживает своевременное принятие решений и устойчивое управление ресурсами. В статье освещаются ключевые технические соображения, от калибровки датчиков до решений по хранению данных, и предлагаются тематические исследования, демонстрирующие, как система помогает обнаруживать аномалии, прогнозировать риски и сохранять здоровье экосистемы вдоль северной части Каспийского моря.

Ключевые слова: Информационная система мониторинга окружающей среды, Северный Каспий, датчики и сенсорные сети, дистанционное зондирование, анализ данных (большие данные), прогностические модели, устойчивое управление ресурсами, качество воды и загрязнение.

КАСПИЙ ТЕҢІЗІНІҢ СОЛТҮСТІК БӨЛІГІНІҢ ЖАҒАЛАУЫНДА ҚОРШАҒАН ОРТА МОНИТОРИНГІНІҢ АҚПАРАТТЫҚ ЖҮЙЕСІН ДАМЫТУ

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Аңдатпа. Бұл жұмыста Каспийдің солтүстік жағалауына бейімделген Экологиялық Мониторингтің Ақпараттық Жүйесін (ЭМАЖ) жобалау және енгізу бойынша кешенді зерттеу ұсынылған. Жүйе судың сапасы, биоәртүрлілік және көмірсутектердің ластануы сияқты маңызды экологиялық параметрлерді бақылау үшін in situ сенсорлық желілерін, спутниктік қашықтықтан зондтауды және болжамды аналитиканы біріктіреді. Модульдік архитектура икемділік пен ауқымдылықты қамтамасыз етеді, нақты уақыт режимінде деректерді жинау мен өңдеуді жеңілдетеді. Жоба осы аймақтағы бірегей экологиялық мәселелерді, соның ішінде теңіз деңгейінің ауытқуын, мұнай өндірудің антропогендік әсерін және климаттың әсерінен тіршілік ету ортасының өзгеруін қарастырады. Мүдделі тараптарды—мемлекеттік органдарды, салалық операторларды және жергілікті қауымдастықтарды-үздіксіз деректер ағындары мен визуалды аналитикамен қамтамасыз ете отырып, ЕМІ уақтылы шешім қабылдауды және ресурстарды тұрақты басқаруды қолдайды. Құжатта сенсорларды калибрлеуден бастап деректерді сақтау шешімдеріне дейінгі негізгі техникалық ойлар көрсетілген және жүйенің ауытқуларды анықтауға, тәуекелдерді болжауға және Каспийдің солтүстік бөлігіндегі экожүйелердің денсаулығын сақтауға қалай көмектесетінін көрсететін жағдайлық зерттеулер ұсынылған.

Түйін сөздер: Қоршаған ортаны бақылаудың ақпараттық жүйесі, Солтүстік Каспий, датчиктер мен сенсорлық желілер, қашықтықтан зондтау, деректерді талдау (үлкен деректер), болжамды модельдер, ресурстарды тұрақты басқару, су сапасы және ластану**.**