Article

Development of sensor systems for flood water monitoring and alerting

Adilbek Sarsenov* [1], Lyazzat Ilipbayeva* [2], and Ulzhalgas Seidaliyeva [3]

[1]Department of Electrical Engineering, Electronics and Telecommunications, IITU University, Almaty, Kazakhstan

[2]Department of Electronics, Telecommunications and Space Technologies, Satbayev University, Almaty, Kazakhstan

[3]Metropolitan College (MET), Boston University, Boston, MA 02215, USA

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Abstract

This study addresses the systematic prediction of river water levels in Kazakhstan via hydrological computations, which are essential for forecasting water-related events and formulating plans for sustainable water resource management. Particular focus is placed on the significance of prompt and efficient monitoring of river dynamics to alleviate natural disasters such as floods and mudflows, especially in high-risk places like Almaty, situated in geologically unstable mountainous landscapes. The research focuses the potential of intelligent sensor-based monitoring systems that can gather real-time data on water levels, precipitation, soil moisture, and various environmental conditions. Systems integrated with artificial intelligence and data analysis can substantially augment decision-making processes, facilitate early warning mechanisms, and boost the precision of forecasts. This method ultimately protects natural ecosystems and local communities from the detrimental effects of hydrological hazards.

Keywords: floods, water level prediction, affordable innovative sensors, devices, water level observation, warnings.

I. Introduction

Seasonal floods continue to cause significant hydrological difficulties, presenting ongoing threats to infrastructure, ecosystems, and public health [1], [2]. River water levels are systematically forecast using hydrological calculations, which are essential for predicting water events and developing sustainable water resource management strategies. Timely and effective monitoring of river dynamics is key to reducing the risk of natural disasters such as floods and mudflows, especially in vulnerable regions such as Almaty, located in geologically unstable mountainous terrain.

*Corresponding author: adilbeksar@gmail.com
Email: adilbeksar@gmail.com ORCID: 0009-0001-6937-1390
Email: l.ilipbayeva@satbayev.university ORCID: 0000-0002-4380-7344
Email: useidali@bu.edu ORCID: 0000-0002-7190-6753

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The intricacy of seasonal flooding necessitates new strategies that transcend conventional procedures. Progressive techniques increasingly depend on sophisticated monitoring technology that facilitate preemptive reactions and informed decision-making. Contemporary sensor-based systems provide the instantaneous acquisition of essential environmental data, encompassing water levels, precipitation, and soil moisture. By integrating these data collection with meteorological projections, authorities can precisely anticipate possible flood disasters and disseminate early warnings. These predictive capabilities not only improve prediction accuracy but also substantially mitigate threats to local residents, infrastructure, and active building projects. So, integrating sensor networks with artificial intelligence and data analytics can help create a more robust water management system [3], [5], [6]. This new strategy ensures rapid responses to emerging risks, strengthening the protection of natural ecosystems and enhancing public safety and well-being.

II. Related works

A. Sensor and System Analysis for Floodwater Monitoring

Floods continue to be one of the most devastating natural disasters globally, necessitating precise monitoring and early-warning systems. In recent decades, researchers have progressively adopted low-cost, real-time sensor networks to monitor water levels, precipitation, and hydrological variables. In contrast to conventional manual gauging stations, these technologies provide continuous monitoring and automatic responses, markedly diminishing human and infrastructural susceptibility.

A prevalent method utilizes ultrasonic sensors for the assessment of water levels. Ultrasonic devices function based on echolocation, releasing high-frequency sound waves that reflect off the water's surface and return to the sensor. The duration between transmission and reception serves as an indicator of water depth. Multiple studies illustrate its practicality owing to cost-effectiveness, seamless integration with microcontrollers, and versatility in remote areas without reliable grid connectivity. Castillo-Effen et al. created a preliminary flash-flood alarm system utilizing wireless sensor networks (WSNs), in which ultrasonic modules were integral to the detection methodology, effectively relaying prompt notifications to authorities and local inhabitants [5]. Abolghasemi and Anisi emphasized that the integration of ultrasonic monitoring with compressive sensing techniques could diminish energy usage in extensive remote flood-monitoring operations [3], [4].

In addition to ultrasonic devices, LiDAR sensors (Light Detection and Ranging) have become prominent for high-precision surface surveying in flood scenarios. LiDAR functions by producing laser pulses and assessing the time delay of reflected signals, achieving millimeter-level vertical precision in surface elevation. LiDAR-derived digital elevation models (DEMs) are integral to flood risk mapping and hydraulic modeling processes, since their high vertical resolution diminishes uncertainty in predicting inundation extents [7]. Despite the higher cost of LiDAR hardware relative to ultrasonic sensors, its resilience to wind-induced turbulence and ambient noise interference provides significant advantages for open-water detection. Numerous evaluations on IoT-based flood monitoring identify LiDAR as a potential sensor within integrated sensor suites for assessing water level, precipitation, and flow rate [8].

Raw sensor data becomes actionable only when integrated with smart forecasting models. In flood forecasting literature, data assimilation techniques, particularly versions of the Kalman filter family, are extensively employed to incorporate sensor readings into models for real-time prediction correction. Gong et al. (2023) introduce a distributed hydrological model employing ensemble Kalman filtering to integrate observed discharge into model states and diminish forecast error [9]. Hybrid communication systems are crucial for transmitting sensor data to processing hubs without latency. Conventional systems frequently depended on GSM or SMS modules; contemporary studies investigate low-power wide-area networks (LPWAN) such as LoRaWAN or NB-IoT in challenging environments to ensure reliable communication [8].

Sensor fusion, which combines hydrodynamic or statistical models with heterogeneous data streams (such as ultrasonic, LiDAR, and rain gauges), is another major approach. Model bias correction and unobserved state estimation are made possible by assimilation frameworks based on EnKF or hybrid Kalman filters. For instance, research using EnKF to combine in-situ measurements and remote sensing (such as SAR flood maps) demonstrates enhanced flood extent representation and increased predictive performance in floodplain models [10].

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B. Wireless Sensor Networks for Flash-Flood Alerting

Wireless Sensor Networks (WSNs) have become an important part of early warning systems for flash floods, offering near-real-time, distributed environmental monitoring in areas that are sensitive. A WSN architecture was proposed by Castillo-Effen et al. (2004), who started work in this field by monitoring hydrological factors and sending out alarms as floods build. Autonomy, resilient mesh routing, and ongoing monitoring in remote areas are the main features of their technology [5]. Over the following years, research has significantly improved the system's capabilities. According to some studies, WSN nodes can use simple forecasting methods using regression models or polynomial extrapolation to predict the level of impending flooding using only local sensor data [11].

While wireless sensor networks (WSNs) and ultrasonic sensors are the focus of much flood monitoring research, lidar-based systems can utilize similar concepts. Both technologies are designed to record water level fluctuations in real time and transmit them to early warning or forecasting systems. These methods are complemented by lidars such as TF-Luna, which offer millimeter-level accuracy, robustness, and the ability to operate in low-light conditions where conventional ultrasonic sensors may be ineffective. When combined with WSNs, lidars can serve as high-precision nodes that improve the data quality of forecasting models. Moreover, the integration of lidar measurements with hydrological and meteorological information is fully consistent with the trend observed in the literature toward multimodal forecasting systems. Because lidar provides more accurate measurements and contributes to the overall goal of proactive flood risk management, it is not only a complementary technology but also a significant improvement.

III. Experimental work

A. Designing and prototyping a system for flood monitoring and early warning

To assess the feasibility of the proposed monitoring strategy, a preliminary laboratory experiment was conducted. An HC-SR04 ultrasonic sensor was installed above the reservoir and precisely oriented so that its probe faced directly down toward the water surface [12]. The sensor was configured to continuously measure the distance to the water, autonomously recording changes as the water level rose or fell. The measurements were processed and graphically displayed, providing a clear visualization of temporal changes. Figure 1 shows an example of the recorded water level fluctuations during a specific experiment. This preliminary experiment not only confirmed the sensor's ability to track liquid level fluctuations but also laid the foundation for future improvements. Future versions may incorporate additional sensors and modules to develop a more robust prototype capable of supporting a fully functional flood warning system.

Figure 1. Calculating distance with the HC-SR04 ultrasonic module

This technique allows for continuous monitoring of water-level fluctuations while accounting for potential influencing factors such as evaporation, surface waves, and external disturbances. Prior to the experiment, the sensor was calibrated to ensure the accuracy and reliability of the obtained results [13].

The graph illustrates data obtained from the HC-SR04 ultrasonic sensor, which continuously records the distance to the water surface in the container. The horizontal axis (X) represents the timeline of successive measurements,

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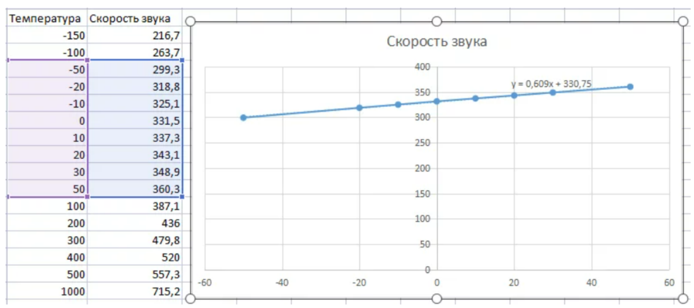
while the vertical axis (Y) indicates the distance between the sensor and the water surface. At the beginning of the experiment, a decrease in distance is observed, corresponding to an increase in the water level. Subsequently, the line gradually rises, reflecting a reduction in the level. In the middle and towards the end of the sequence, fluctuations become noticeable, including a sharp spike likely caused by air bubbles or surface waves. Overall, the graph clearly demonstrates the dynamics of the water level in the container, enabling analysis of the process of adding or removing water [14].

It is important to note that the speed of sound in air depends significantly on temperature. At a temperature of +20°C, the speed of sound is approximately 343 m/s, whereas at −20°C it decreases to about 318 m/s. Thus, a temperature variation of 40°C results in nearly a 7% change in velocity, which, at a distance of 1 m, may lead to an error of about 7 cm. Such an error is significant and exceeds acceptable measurement tolerances. To minimize this issue, it is essential to account for the temperature dependence of the speed of sound. Within the range of −50°C to +50°C, this dependence can be approximated as a linear function:

$$V = 0.609 \cdot T + 330.75$$

where V is the speed of sound in air (m/s), and T is the ambient temperature (°C), Figure 2.



Температура	Скорость звука
-150	216,7
-100	263,7
-50	299,3
-20	318,8
-10	325,1
0	331,5
10	337,3
20	343,1
30	348,9
50	360,3
100	387,1
200	436
300	479,8
400	520
500	557,3
1000	715,2

Figure 2. Graph of sound velocity versus temperature.
(Note: the figure contains original labels in Russian as it is a direct screenshot from the experiment; corresponding English translations are shown below:
"Температура" — Temperature, "Скорость звука" — Sound Speed)

The Arduino IDE's Serial Monitor continuously displays sequential measurements of the distance to the water surface, as detected by the TF-Luna LiDAR sensor, Figure 3. These measurements are updated in real time and presented in centimeters, reflecting the dynamic changes in the liquid level within the container. At the beginning of the observation, decreasing distance values were recorded, corresponding to an increasing water volume. As monitoring continued, fluctuations in the measurements became apparent. These variations may be attributed to water surface oscillations, the presence of air bubbles, or changes in the surface's reflectivity affecting light wave reflections [15]. Additional discrepancies could also result from sensor measurement irregularities or alterations in the water properties over the prolonged observation period.

As the medium's parameters fluctuate, the measured distance increases, indicating a decrease in the liquid level. In the central portion, pronounced oscillations and abrupt jumps in values are observed, which may be attributed to mechanical wave activity, the presence of air bubbles, or variations in the liquid surface's reflectivity. The use of the TF-Luna LiDAR for measuring water levels in containers demonstrates high accuracy and stability, establishing it as a reliable tool for automated monitoring and control in both engineering and scientific water-level applications.

B. Arduino-Based System for Real-Time Meltwater Measurement

To further enhance the understanding of autonomous hydrological monitoring, a dedicated system for meltwater surveillance has been developed. As illustrated in Figure 4, this system is centered around an Arduino Uno microcontroller and integrates multiple sensors, a solar energy harvesting module, batteries, and a GSM communication unit.

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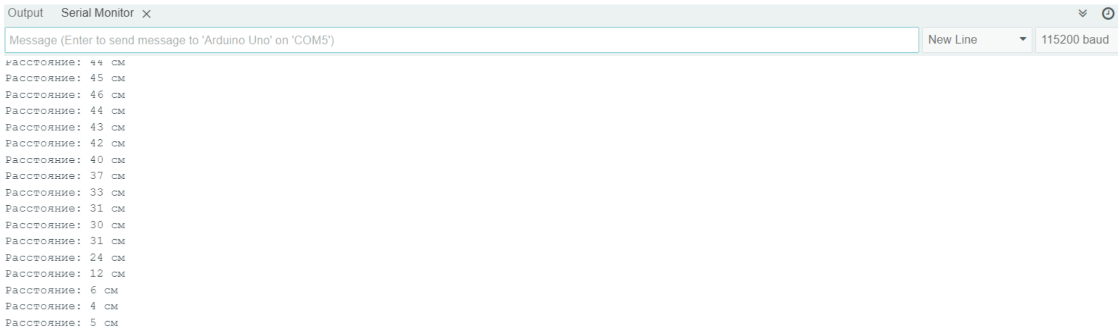

Figure 3. Measurements of the TF-Luno Lidar sensor. (Note: "Расстояние" — Distance; "см" - cm)

This configuration allows for continuous, contactless monitoring of water levels under varying climatic conditions. The core sensing element, the HC-SR04 ultrasonic transducer, measures water depth by emitting ultrasonic pulses and analyzing their echoes. Data are transmitted in real time via the GSM module, enabling remote users to receive alerts or access measurements through text messages or server connections. This remote monitoring capability ensures timely detection of significant water level fluctuations. Overall, the proposed platform provides a solar-powered, autonomous solution for long-range surveillance of meltwater stores, combining reliable data acquisition with immediate reporting functionalities.

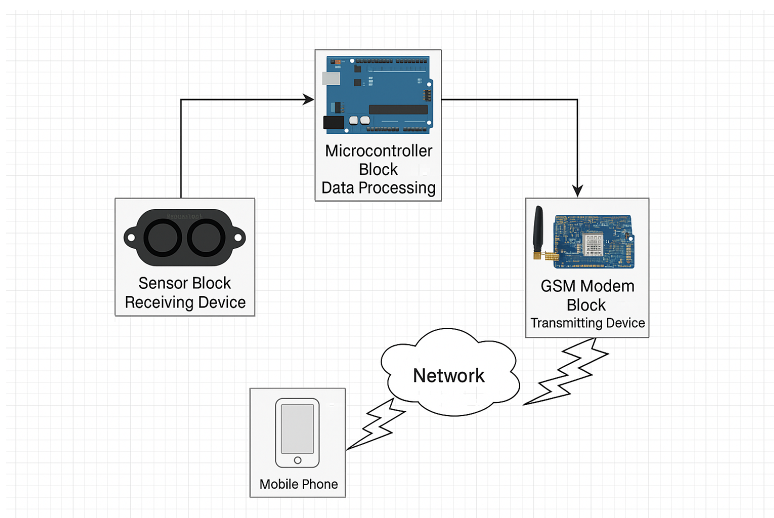

Figure 4. Block diagram of the system

The presented system provides autonomous monitoring of meltwater levels through an integrated remote sensing platform. Real-time measurements are achieved using laser rangefinding, while an Arduino microcontroller processes the LiDAR data to analyze fluctuations and detect significant changes. When critical thresholds are reached, automated notifications promptly inform operators of potential flooding risks.

Reliable long-range communication is maintained via a SIM900L GSM modem, supporting text messages, calls, and cloud-based data transmission, Figure 5. While cellular networks are generally sufficient, alternative wireless technologies such as LoRa or Wi-Fi can enhance connectivity in remote or challenging environments. The system's

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flexible design allows for the integration of additional environmental sensors and IoT services, improving predictive capabilities by incorporating parameters such as soil moisture, precipitation, and barometric pressure. Alerts are delivered to operators on any device through SMS, phone calls, app notifications, or a web dashboard [16].

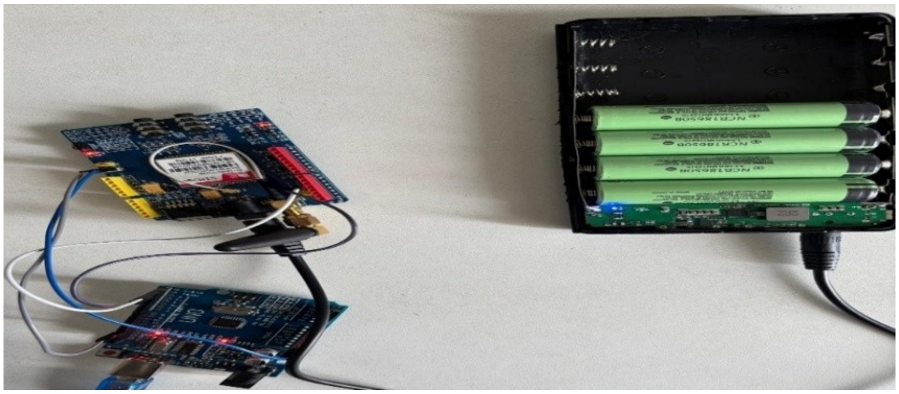

Figure 5. Establishing Communication Between Arduino Uno and GSM 900L

This combination of autonomous operation, flexible communication, and modular integration ensures timely warnings regardless of location. The modular architecture also facilitates the adjustment of system settings, incorporation of new sensors, and customization for diverse climatic and geographical conditions. Overall, the adaptable design provides reliable monitoring and prompt notification, making it suitable for a wide range of deployment scenarios.

To ensure fully autonomous operation, the system is equipped with a rechargeable power source, consisting of a battery pack built from a single 18650 cell. This configuration enables the device to function in remote or hard-to-access locations where conventional electrical power is unavailable. The solar-powered indicator screen displays the battery charge status, facilitating real-time monitoring of the system's energy availability. Interconnecting wires and USB cables transmit both power and data between components, establishing a reliable and stable monitoring framework.

In parallel, the Arduino IDE serial monitor, illustrated in Figure 6, visualizes the exchange of AT commands with the SIM900 GSM module. The output demonstrates a complex yet dynamic communication pattern, with alternating sequences of longer and shorter command responses, reflecting the ongoing interaction between the microcontroller and the GSM module.

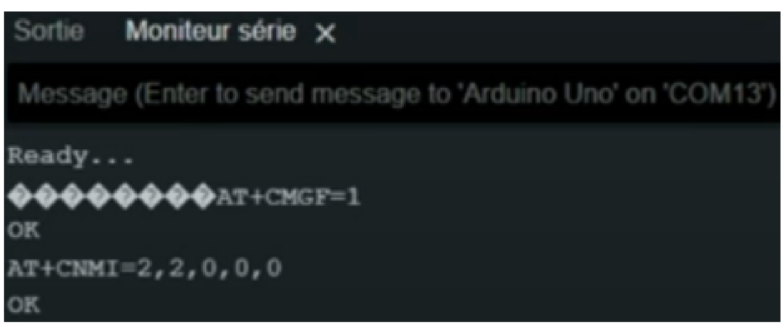

Figure 6. Serial Monitor port in the Arduino IDE

Together, these features provide a robust and self-sufficient platform capable of continuous data acquisition and remote connectivity, even in isolated environments.

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Upon powering on the device, the console displays the message "Ready. . . ", indicating that the SIM900L module is prepared for operation. The initialization process begins with the AT+CMGF=1 command, which switches the module to SMS text mode; successful execution is confirmed by the "OK" response. Subsequently, the AT+CNMI=2,2,0,0,0 command is issued, configuring the module to immediately display incoming messages in the terminal. The "OK" response verifies that the settings have been applied correctly, Figure 7.

Following initialization, the SIM900L module is fully operational, capable of sending and receiving SMS messages. Its integrated management functions enable seamless incorporation into automated monitoring and notification systems. When combined with the TF-Luna LiDAR and the HC-SR04 ultrasonic sensor, the platform achieves high-precision, multipoint assessment of water levels, leveraging both laser and ultrasonic measurements to enhance reliability and accuracy.

Moreover, the SIM900L supports incoming SMS notifications, allowing the system to respond to changing conditions and receive remote control commands. The provided code facilitates verification of the sensor and GSM module functionality. By employing GSM communication, the system can maintain monitoring and reporting capabilities even in remote locations lacking wired network infrastructure, thereby ensuring continuous and reliable water level surveillance.

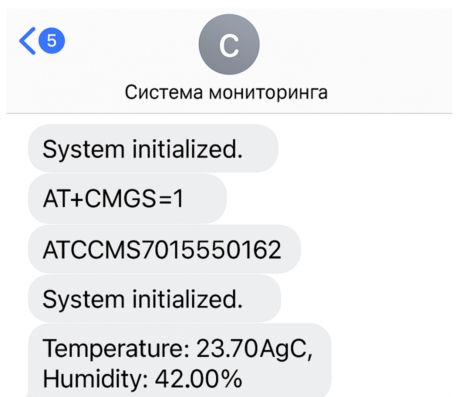

Figure 7. Result of receiving SMS on a mobile phone

The proposed water level monitoring system integrates a range of technologies to accurately measure and respond to variations in liquid levels. Central to the system is an ultrasonic sensor, which employs echolocation to precisely determine the distance to water surfaces. Temporal variations in these measurements can indicate potential flooding conditions. The sensor data are transmitted to an Arduino microcontroller for processing, where they are compared against predefined thresholds. When critical limits are exceeded, the system automatically triggers an alarm, promptly notifying relevant stakeholders. Beyond simple threshold detection, the system analyzes data trends to anticipate changes, thereby enhancing monitoring and response effectiveness proactively, Figure 8, [17].

For remote operation, a GSM module transmits measurements and alerts in real time, keeping distant users continuously informed via SMS. In emergency situations, the module can automatically contact relevant authorities, providing time-sensitive information to facilitate rapid mitigation efforts. Energy efficiency has been incorporated from the outset, with a solar panel charging the system's power cells to maintain autonomous operation regardless of external power availability. Energy-saving components further extend maintenance intervals, a critical feature for deployment in remote or difficult-to-access locations.

In summary, by integrating measurement, processing, real-time transmission, and autonomous energy management, the proposed system offers a reliable solution for water level monitoring. It not only tracks fluid levels with high precision but also mitigates potential flood damage through timely alerts and prepared response strategies.

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Figure 8. Meltwater monitoring system

The components of the water level monitoring system were carefully assembled to form the core device, integrating all essential functions. The system comprises an Arduino Uno microcontroller, a GSM module for remote communication, an HC-SR04 ultrasonic sensor for distance measurement, a power supply consisting of 18650 batteries, and an external battery supported by a solar panel. The inclusion of a solar-powered battery enables autonomous operation by reducing dependence on external energy sources.

At regular intervals, the HC-SR04 ultrasonic sensor connected to the Arduino Uno measures the distance between the sensor and the water surface, thereby determining the liquid level. The microcontroller processes the acquired data, comparing it against predefined thresholds. When critical water levels are detected, the GSM module transmits urgent notifications either to a central alert system or directly to the mobile devices of responsible personnel. The wired connections between components ensure reliable data transmission and efficient power management. The microcontroller coordinates incoming signals, regulates the power supplied to peripheral modules, and performs the logical operations necessary for proper system functionality. Additionally, a backup battery pack safeguards the device against potential power interruptions.

The development of such autonomous monitoring and alert systems is essential for flood prevention and the mitigation of natural disaster impacts. The use of energy-efficient sensors combined with wireless communication technologies enhances measurement accuracy while improving the reliability of data transmission. The implementation of similar solutions in water management infrastructure could significantly increase operational safety and reduce the risk of flooding emergencies.

IV. Conclusion

In summary, this study tried to propose an environmental monitoring system using readily available sensors. A comparative experiment was conducted to evaluate the performance of two devices: the TF-Luna lidar sensor and the HC-SR04 ultrasonic sensor. The main objectives of the experiment were to evaluate accuracy, robustness to external factors, response to temperature fluctuations, distance measurement to the water surface, and data processing speed.

The analysis of the experimental results demonstrated the effectiveness of low-cost sensors for monitoring water levels during seasonal floods. The development and deployment of such solutions, leveraging modern microcontrollers

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and sensor technologies, can substantially enhance the efficiency of water body monitoring. These systems enable continuous, real-time data acquisition and, when critical water levels are reached, automatically issue alerts to emergency services and the public via SMS, mobile applications, or other digital communication channels.

The integration of affordable sensor solutions with automated warning mechanisms represents a promising approach to improving infrastructure resilience and mitigating the risks associated with floods. This is particularly important for regions that are regularly affected by seasonal flooding.

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