Sustainable urban environment management: an approach for disaster mitigation through water and weather monitoring system for river environment in Bekasi watershed, Indonesia

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Abstract. This study presents a sustainable approach to urban environment management, focusing on disaster mitigation in the Bekasi watershed, Indonesia. Utilizing a low-cost IoT-based system, the integration of automated water level recorders (AWLRs) and automatic weather stations (AWS) enables real-time monitoring of hydrometeorological conditions. By providing continuous data on water levels and weather parameters, the system enhances flood forecasting and supports timely disaster mitigation efforts in densely populated urban areas. The scalable and affordable design promotes sustainability and resilience in flood-prone regions, contributing to better urban water management and community safety.
Key Words: forecast, real-time, sustainable, urban resilience, wind speed sensor.

Introduction. Floods and inefficient water usage are global challenges that demand quick and effective actions to minimize their impact on people and infrastructure. The effects of climate change and urbanization have not only increased hydrometeorological disasters but also exacerbated the strain on water resources, underscoring the need for smarter, more efficient management solutions (Putri et al 2022; Bernardes et al 2023). Developing integrated river water level and weather monitoring systems is essential in catastrophe risk management (Thakur & Devi 2024).

In water resource management, early warning systems aim to mitigate damage from unexpected variations in water levels. These systems rely on the collaboration of multiple disciplines, including hydrology, meteorology, engineering, and informatics, to develop solutions. The proposed system utilizes Internet of Things (IoT), cloud computing, and big data analysis to enhance early warning capabilities and optimize water conservation efforts (Pianto et al 2023; Hakim et al 2024).

Various water level monitoring systems have been developed, including field gauges (Paoletti et al 2023), automated water level recorders (AWLR) and telemetry systems (Soehartanto et al 2023). Traditional water level monitoring is typically conducted manually, a time-consuming process that only sometimes provides real-time or location-specific data (Woo et al 2023), and is also susceptible to human errors (Sabbatini et al 2021). Additionally, such monitoring is often not integrated with weather monitoring systems that track climate parameters. Hydrometeorological factors - such as temperature, humidity, evaporation, and rainfall - play a significant role in climate change risks (Kliengchuay et al 2024).

A smart water management system that integrates water level and weather monitoring can help optimize water conservation, especially in urban areas where resource demand is high. Research has been conducted to develop systems that integrate water level monitoring with weather sensors and advanced communication technologies. The World Meteorological Organization (WMO) has recognized systems such as the Automatic Weather Station-Low Cost (AWS-LC) (Ioannou et al 2021) which uses low-cost, build-it-yourself systems with Arduino-based microcontrollers and loggers, offering significant benefits for hydrological data collection. Other systems, use such as ArduHydro (AH) (Galli et al 2024) and ESP32-based microcontrollers (Indriyani et al 2024), provide real-time data collection and performance evaluation for flood monitoring.

Various institutions, including the Japan River Bureau, have adopted low-cost sensors like MaxBotix ultrasonic sensors with a 10-meter measurement range for flood detection (Purkovic et al 2019). Bresnahan et al (2023) demonstrated how combining MaxBotix ultrasonic rangefinders with real-time displays and microcontrollers can yield high-resolution water level measurement. In supporting the acquisition of real-time data, IoT technologies are crucial, as they enable low-power, ultra-narrowband communication for monitoring systems (Knight et al 2021).

Watersheds in Indonesia, particularly the Bekasi watershed, face significant flood risks due to dense population and green land conversion (Supangat et al 2023; Fitriyati et al 2024). However, such systems are still lacking, particularly in Indonesia. This study aims to design and implement a low-cost, IoT-based monitoring system that integrates AWLR and automatic weather stations (AWS) for real-time flood monitoring and disaster mitigation in the Bekasi watershed, Indonesia. The system monitors water levels and climatic parameters to provide early warnings and help mitigate flood risks. This study aims to design and implement a low-cost, IoT-based monitoring system integrating AWLR and AWS for real-time flood monitoring and disaster mitigation in urban watersheds at Bekasi, Indonesia. The system is planned to monitor water levels and climatic parameters, providing early warning capabilities to mitigate flood risks. This research emphasizes the importance of cost-effective, scalable solutions for disaster preparedness in densely populated, flood-prone areas, contributing to improved water management strategies and enhancing community resilience. The system's construction, data communication, and equipment maintenance all prioritize cost-efficiency. By integrating hydrometeorological data into disaster risk management, this technology offers a novel approach to flood mitigation. The warning system is based on previous research that outlines the alert phases leading to a risk signal (Dswilan et al 2021). Additionally, the use of a wireless, portable microcontroller ensures that the prototype is highly portable and suitable for meteorological and flood data exchange (Mdegela et al 2023). Based on this explanation, the aims of this research are as follows: (1) to introduce IoT-based flood disaster mitigation devices, specifically AWLR and AWS, (2) to analyze the performance of AWLR and AWS devices, and (3) to assess the effectiveness of the devices' output displays in conveying information to users.

Material and Method

Description of the study sites. This study was conducted on October to December 2023 in the Bekasi watershed with an area of 9444.886 ha (Nurhayati 2009). This watershed is included in the administrative area of Bekasi Regency, Bogor Regency and Bekasi City, West Java Province. The Bekasi watershed is divided into 2 sub-watersheds, namely the Cikeas sub-watershed and the Cileungsi sub-watershed (Prihartanto & Ganesha 2019) with various types of land cover in the form of settlements, industry, mining, and shrubs (Effendi et al 2021), and has 3 major rivers (Bekasi River, Cikeas River, and Cileungsi River). The Bekasi watershed is very important because it is a source of clean water for residents and industrial activities in the province. However, the watershed is prone to flooding during the rainy season (Prihartanto & Ganesha 2019), especially the area around the confluence of the Cileungsi and Cikeas Rivers. The main causes of these flood events are high rainfall and land use change in the upper Bekasi watershed (Kadri et al 2011). The Bekasi watershed was chosen as the location for testing the tool because the size of the watershed is not too large, it experiences flooding every year, and has a high population density and industrial activity.

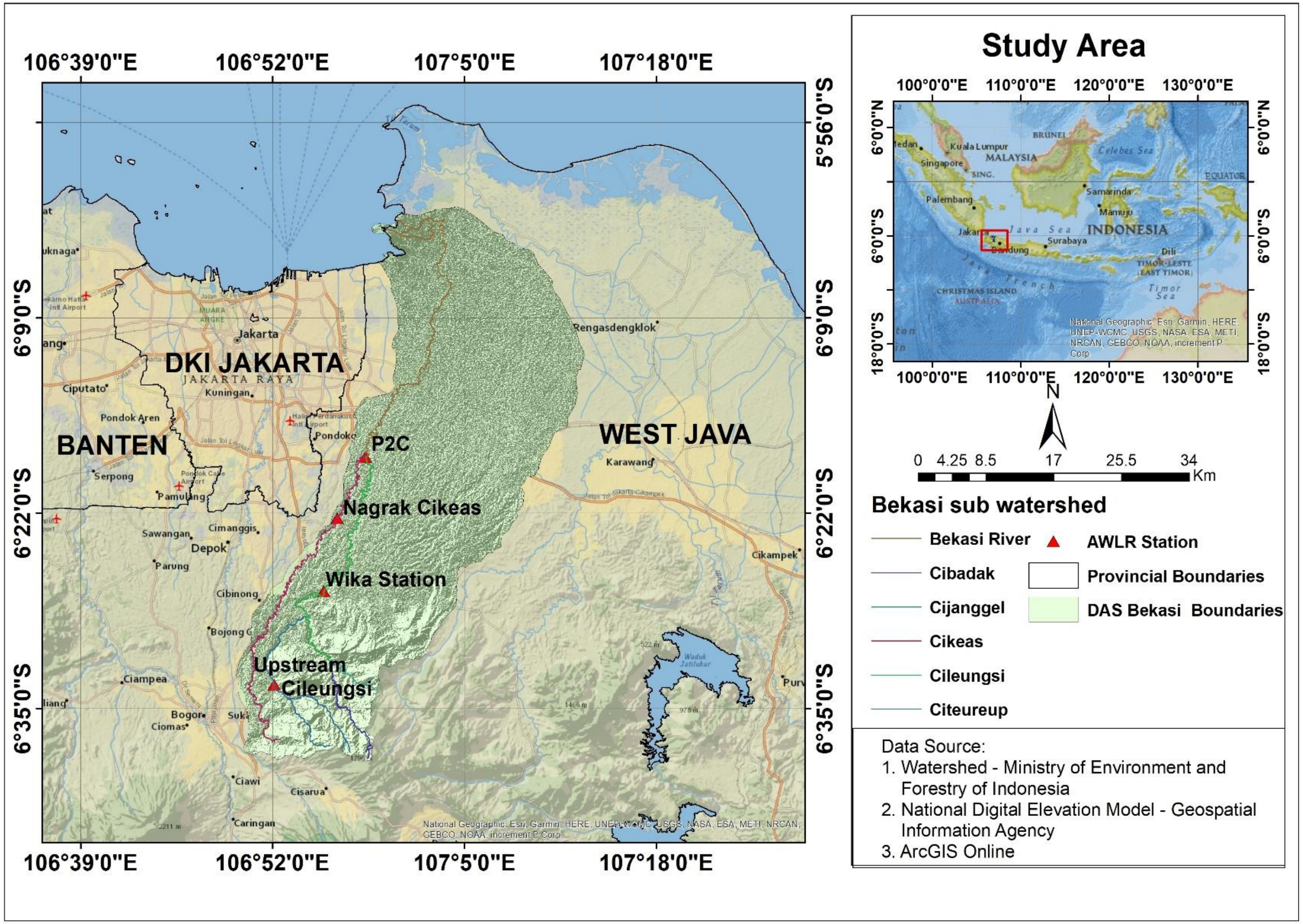

Figure 1. Research location in Bekasi watershed, Indonesia.

Sensor and device used. This study was considered some sensors and devices for establishing the instrument for monitoring water levels and climatic parameters. All devices and their function used in this research are outlined in Table 1.

Table 1

Sensor and device specification

No	*Sensor / Devices*	*Function*
	AWLR sensor	
1	Distance ultrasonic sensor (MaxBotix)	Measure of water level
	AWS sensor	
2	PR-3001-GYL-N01	Rain sensor
3	ZGCJ Wind Speed Sensor	Wind speed and direction sensor
	Supporting devices	
4	ESP/32	Micro control unit (MCU)
5	USB Modem 4G	Network access point
6	Web/database Host	Data storage / Viewer real time
7	Solar Cell 10WP	Energy source
8	Battery 12VDC 4AH	Power storage

The devices in Table 1 are designed to identify specific patterns that can serve as early indicators of upstream-to-downstream flooding occurrences. To support this process's smooth and durable operation, these devices' power consumption characteristics and data intervals need to be carefully considered, as described in Table 2.

Table 2

System features

No	*Features*	*Characteristics*
1	System working voltage	5 Volt DC
2	Power consumption:	
	– sleep mode	0.05 watt
	– measurement mode	1 watt
3	Measurement frequency	Every 10 minutes

Research implementation stages and methodology. In assembling the water level and weather monitoring instrument, six steps were taken, namely (i) system design, (ii) prototype development, (iii) data collection and sensor calibration, (iv) data analysis, (v) integrating system, and (vi) system testing and validation. In general, the working system in this device is organized in the form of a block diagram, which can be seen in Figure 2.

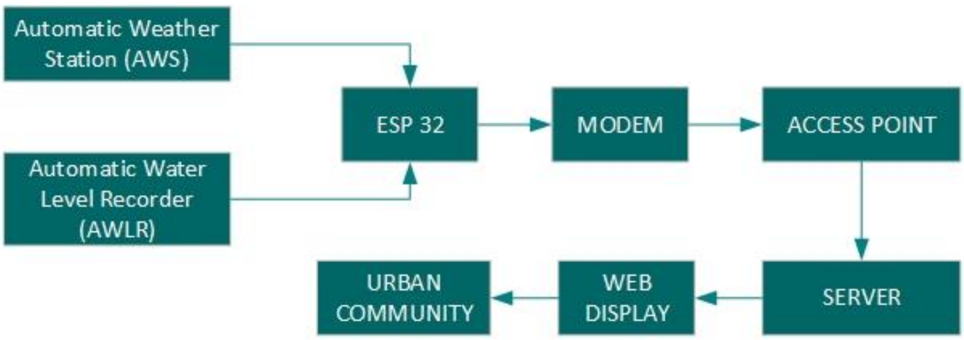

Figure 2. The research block diagram.

System design. A monitoring and control system design combines an AWLR system architecture (Pianto et al 2023) and AWS to collect meteorological data using a telemetry system (Winarno et al 2021). Continuous data collection has been conducted using the ESP32 microcontroller, which has also been utilized in river research (Pramono et al 2023) and as a weather monitoring device (Babalola et al 2022). In this stage, before conducting measurements using the microcontroller, quality control is performed on the pins used in the measurements, as well as on electrical parameters such as voltage, current, and power consumption (Pratama & Kiswantono 2023). The collected data is then relayed to the server via an Internet modem and access point. The data and calculations are displayed in the web-based platform using JavaScript and PHP programming languages.

Prototype development. The prototype monitoring system's development utilizes MaxBotix ultrasonic sensor, PR-3001-GYL-N01 Rain Sensor, and ZGCJ Wind Speed Sensor. Integration of sensors enables the measurement of both hydrological and meteorological parameters. These sensors possess technical specifications that allow for accurate and low-cost measurements (Pearce et al 2024), including accuracy, measurement range, and resistance to environmental conditions. This prototype must be reliable in its usage and recorded over the long term, considering its design, connections, data storage, and analysis (Fausto et al 2020).

Data collection and sensor calibration. In data collection, water level and temperature sensor data are acquired in real-time and archived in a database for subsequent analysis. The recording interval for data collection is set at 1-2 seconds, and real-time data are displayed on a web-based monitoring system within the laboratory. The test was implemented during the first data collection process. It is designed to calibrate devices or instruments to identify the slightest possible data error. The errors being addressed include inaccuracies in data resulting from real-world situations, flaws in data structure, and performance-related problems. Calibration procedures are performed prior to the permanent installation of instruments at designated sites to ensure the accuracy and reliability of the data recording results. The sensor calibration process involves continuous readings of sensor outputs on a laboratory scale to calibrate pressure, temperature, and humidity measurements. Additionally, in the calibration process, reference water levels are established within the calibration tank (Pianto et al 2023), while weather conditions (including wind speed, air temperature, and humidity) are referenced from local climate stations (KP2C station). A confidence level of 95-98% is targeted for the calibration results (Kerdkaew et al 2024).

Data analysis. The collected data from the AWLR and AWS systems undergo analysis by comparing data from other stations to identify patterns and trends that may indicate potential flood risks. The analysis aims to enhance flood prediction capabilities and improve disaster preparedness measures by examining historical trends and current data. The data calculation is performed using empirical hydrological models, where the river discharge is monitored using Sherman's method, such as employing sensors to track water levels and weather conditions, transmitting data in real-time, analyzing flood risks, and issuing early warnings (Devia et al 2015).

Integrating system. System integration includes using data loggers to capture sensor readings, which are then transmitted to a PC connected to a GSM modem (Figure 3). A web-based platform was developed to simultaneously integrate data collected from the AWLR and AWS systems. The system is a hub to access and analyze the measurement data of ultrasonic and weather sensors in real-time. Data communication to the server is then carried out via a GSM network, so monitoring data can be displayed on a web display or periodic short messages, thus, enabling timely notification to authorities in the event of potential flood risks. This connectivity enables communication with the server and facilitates data display of the monitoring system, ensuring efficient monitoring and response capabilities.

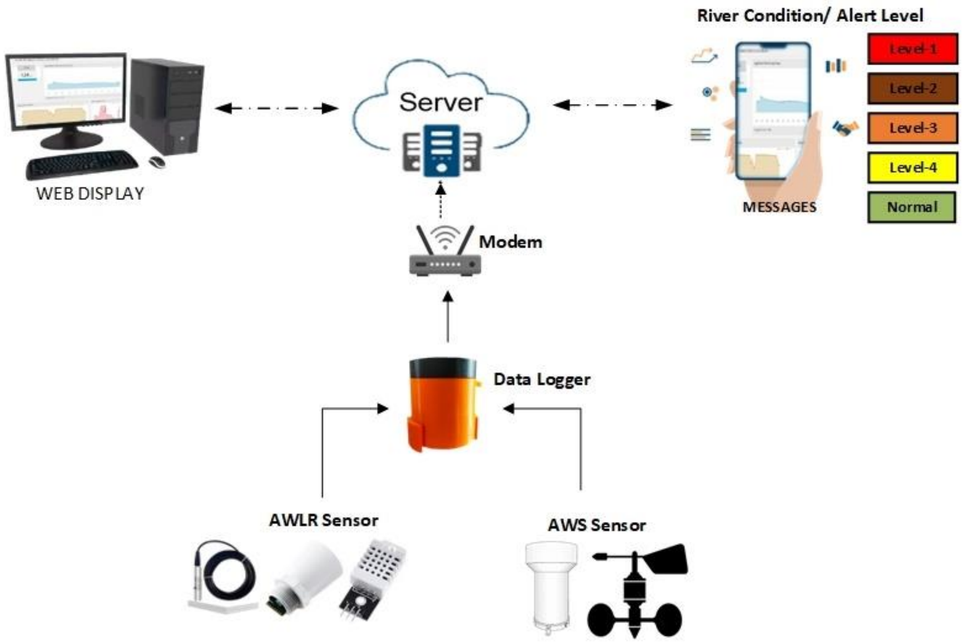

Figure 3. Integrated infrastructure of AWLR and AWS.

System testing and validation. The test and validation of an integrated AWLR and AWS monitoring system involve rigorous procedures to ensure its functionality and reliability in real-world scenarios. Field tests are conducted to verify the system's performance under varying weather and hydrological conditions, involving the testing of sensors in different scenarios. These field trials are crucial for verifying the system's ability to accurately measure water level, air temperature, humidity, and wind speed. Additionally, the system's results are validated by comparing its predictions with historical data and field observations from other stations, assessing its accuracy and reliability. This validation process provides confidence in the system's capabilities and suitability for flood monitoring and early warning applications. Testing of the tool was carried out in the Bekasi watershed, Indonesia on July 2023.

Results and Discussion

***Design of integrated automatic water level and weather monitoring system*.** This research focuses on developing an integrative system that combines water level and weather monitoring for IoT-based disaster mitigation management. The main parameters used in this system are water level data and weather data (rainfall, wind speed, and wind direction). By utilizing this data, the system can recognize patterns that indicate potential flooding on the downstream side. As such, the system will assist relevant parties and communities in disaster mitigation, as well as minimize the negative impacts of flooding and protect against losses that will be incurred. Figure 4 shows the integrated design of the AWLR (Figure 4a) and AWS (Figure 4b). The system employs the ESP32 microcontroller chip (Figure 5) as the central processing unit. This chip possesses functionalities that facilitate the transmission of data without the need for physical connections and allows for Internet access, both of which are crucial in systems that require continuous monitoring in real time. The ESP32 is utilized in this research because it not only provides adequate computational power to process sensor data quickly and efficiently but also supports Wi-Fi and Bluetooth connectivity, enabling wireless data transmission to servers or other devices, as well as integration with mobile devices or other Bluetooth-enabled peripherals. Additionally, the system is linked to the AWS system, which has sensors for measuring rainfall, wind speed, and wind direction. The data is supplied at 10-minute interval and continuously monitored in real-time. The integration of the two systems has been designed in a way that creates a portable instrument with compact dimensions, as shown in Figure 4. The tool's housing is designed to be resistant to weather and rain, and its vivid hues make it simple to detect. The measurement system is equipped with at least one water level sensor (Ultrasonic) and data.

Figure 4. (a) Water level device (AWLR); (b) automatic weather station (AWS) which was tested at the laboratory.

Figure 5. Several instruments are employed to continuously measure the flow of water in streams at observation locations located upstream of the Cikeas - Cileungsi watersheds. The measurement system is equipped with at least one water level sensor (Ultrasonic) and data.

Sensor performance test. The system development process involved a series of tests of sensors placed perpendicular to the water surface, conducted in various water level scenarios. Measurement intervals set to every 10 minutes allowed careful observation of changing conditions, despite the time drift seen in repeated measurements. The stable data pattern indicates that the system has reached the expected level of consistency, providing a solid basis for further development.

The test results of the AWLR sensor demonstrated satisfactory performance, with an error rate of less than 5 cm (Table 3). This confirms the accuracy and dependability of the sensor for future system implementations including measurement. These findings instill trust in the sensor's capacity to accurately gauge water levels, establishing a strong basis for its use in flood monitoring and early warning systems. The next discussion is regarding the AWS sensor test. This is conducted by taking measurements at the same time using 2 different devices and examining whether the values are valid across various repetitions performed, as seen in Table 4.

Table 3

AWLR sensor test

Sequence number	*Height of sensor placement (cm)*	*Height of sensor recorded (cm)*	*Error (cm)*	*Repetition*
1	20	21	1	12
2	50	50	0	12
3	100	100	0	12
4	200	202	2	12
5	300	300	1	12
6	500	501	1	12
7	600	599	1	12

Table 4

AWS sensor test

No	*Sensor*	*Data collect*	*Different value*	*Confidence level (%)*
1	Rain	620	6	99.03%
2	Wind speed	3300	177	94.64%

The expected confidence level of the AWS sensor test by the author is around 90-95%. The validation results from 2 different devices fall within the range of 94.64-99.03% (Table 4). This indicates that the values are still within the allowed scope of confidence level, and these devices are deemed valid for use.

Integrated monitoring system performance*.* The performance of the integrated monitoring system combining AWLR and AWS was validated by monitoring changes in water levels during rain events. The telemetry data test was conducted by measuring the time difference between data acquisition from the devices and data reception on the database server. The data transmission delay from the sensors to the laboratory monitor (approximately 20 kilometers away) ranged from 1 second to 1 minute, still considered real-time monitoring (Chaduvula et al 2021; Soehartanto et al 2023). Internet connectivity is crucial for IoT-based water level monitoring devices. It enables real-time data transmission, rapid analysis and response to flood risks, remote access, and centralized data storage. Without the internet, these devices would not be effective in providing accurate and timely information.

Figure 6 (Note: Rainfall Measurement Stations located in the same area) shows the graph of rainfall data and river water levels from November 1 to 19, 2023. Data from three monitoring stations along the Bekasi River were collected to observe variations in water levels due to rainfall. The stations are assumed to represent the entire Bekasi watershed, with two upstream stations (Cileungsi and Gunungsari) and one downstream station (AWLR KP2C Jatiasih). During the trial period, alert status was recorded three times due to rising water levels downstream (KP2C Jatiasih station) on November 5, 17, and 18, 2023, with recorded water levels of 590 cm, 390 cm, and 410 cm, respectively.

The data graph indicates that the rainfall event on November 4, 2023 resulted in a water level rise on November 5, 2023, as observed at all three monitoring stations. On November 4, 2023, rainfall in the upstream Bekasi watershed reached 24.5 mm, increasing to 46.8 mm on November 5, 2023. The changes in rainfall intensity impacted river water level fluctuations recorded by the AWS and AWLR monitoring systems. At Gunungsari Station (the most upstream position), the water level rise by 218 cm on November 5 at 14:30 WIB. Due to the long river flow distance, downstream water level recordings experienced a time lag, with the highest recorded at Cileungsi Station (350 cm) four hours later, leading to an alert status downstream. Ten hours later, water levels downstream in the Bekasi watershed rose to 590 cm, recorded at KP2C Jatiasih station. Local rainfall in the central Bekasi watershed on November 5, 2023, also increased water levels at Jatiasih and Cileungsi Stations, reaching 590 cm and 350 cm, respectively.

Rainfall in the upstream Bekasi watershed caused flooding in Bekasi City residential areas. Empirical calculations show flood peaks take 5.5 to 6 hours to reach downstream (Prihartanto & Ganesha 2019). Therefore, adding AWLR and AWS monitoring stations in the upstream Bekasi watershed will enhance disaster mitigation time management.

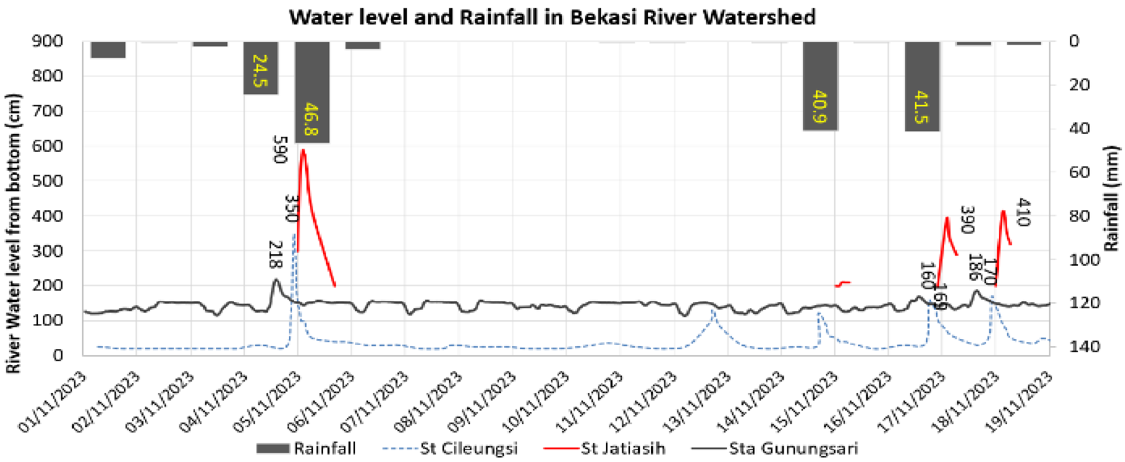

Figure 6. Daily water temperatures recorded throughout the study period.

On November 17-18, 2023, an increase in flood alert status was preceded by rainfall of over 40 mm in the upstream Bekasi watershed, resulting in higher water levels at all three monitoring stations. Although the increase was slight at Gunungsari Station (169 and 186 cm), it directly impacted the water level measurements at Cileungsi Station (160 and 170 cm), leading to an increased alert status downstream in the Bekasi watershed.

Research on flooding in the downstream areas of the Bekasi watershed shows that flood predictions for 2020, 2025, and 2030 indicate an increase of 28.4% from 2020 to 2025 and 26.8% from 2025 to 2030 (Marko & Zulkarnain 2018). This suggests that additional AWLR and AWS monitoring systems are still needed in the Cileungsi and Bekasi watersheds. Correctly placing river height monitoring networks is crucial for an early flood warning system, which occurs routinely in the densely populated downstream areas of the Bekasi watershed due to urban and industrial sectors. The availability of this monitoring system can also be developed by integrating river water quality sensors and cameras for future research. According to a study (Effendi et al 2021), the Cileungsi River is polluted except for the upstream part, while the Cikeas River is in good condition except for the downstream section, and the Bekasi River has a moderate pollution index.

By analyzing rainfall and water level data recorded in the integrated monitoring system, it can be determined that an increase in alert status is directly related to increased rainfall data from the previous and the same day. This system shows a positive correlation between river water level and rainfall graphs with downstream station data (Jatiasih). This demonstrates that the monitoring system implemented by the team provides valuable contributions to the water level observation network in the Bekasi watershed and disaster mitigation efforts.

Establishing an AWLR monitoring network is essential to enhance early warning systems and effectively prepare for flood disasters (Qundus et al 2022; Pranatan et al 2022). Additionally, including various suitable sensors and utilizing IoT technology can significantly improve data accuracy (Langhammer 2023; Susila et al 2023). For the Bekasi watershed and its tributaries, the primary sensors needed are rainfall and river water level sensors. Furthermore, considering the previously assessed pollutant index, including river water quality sensors, would be an ideal choice for environmental monitoring. Implementing an AWLR network in the central area of the watershed will enhance early warning capabilities for heavy rainfall occurrences in the central Bekasi watershed.

The performance test findings of this integrated AWLR and AWS monitoring system demonstrate its ability to promptly detect variations in water levels and weather conditions, thereby enhancing flood forecast accuracy. The technology utilizes past and current data to identify trends that serve as early indicators of floods. Further investigations were conducted to evaluate the system's effectiveness in various settings and conditions and ensure its reliability in real-world scenarios.

Web display. The AWLR and AWS systems are integrated into an information system via the Internet for data communication. Its objective is to streamline data exchange and data access for multiple users. Figure 7 depicts the display of an information system that monitors water level parameters and weather parameters in real-time inside the Bekasi watershed. The system utilizes AWLR and AWS data. The metrics shown on the AWL are crucial for monitoring hydrological conditions and serve as a critical indicator for stakeholders in deciding on flood hazard mitigation in the case of heavy rainfall or a sudden rise in water levels. The AWS parameters encompass air temperature, humidity, rainfall, air pressure, and wind speed, offering a full meteorological data set. This visualization facilitates comprehension of environmental conditions and enables informed decision-making for water resources management and meteorological analysis.

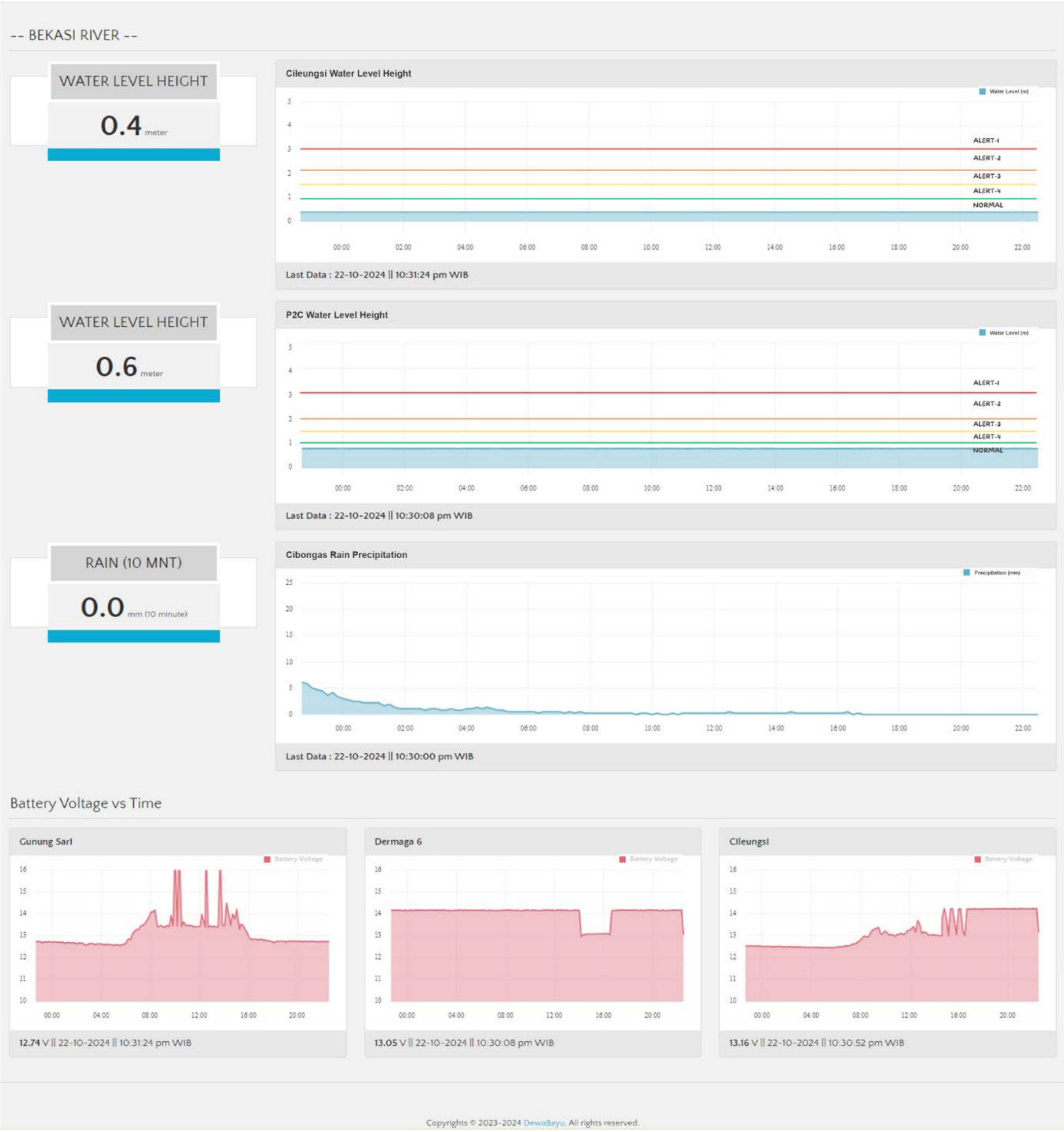

Figure 7. Web display from AWLR and AWS data.

Developing an integrated water and weather monitoring system for the Bekasi watershed demonstrates a sustainable approach to urban environment management. The system uses low-cost IoT technology to address the increasing flood risks in urbanized regions due to rapid land-use changes and climate variability. This system provides a solution by monitoring key parameters - such as water levels and weather conditions - in real-time, which is essential for predicting and managing flood events in the Bekasi watershed.

The design ensures the monitoring system is scalable and cost-effective, making it accessible for widespread use in other urban environments facing similar challenges. The integration of AWLR and AWS enables continuous data collection, which is critical for providing timely alerts and supporting decision-makers in implementing flood mitigation measures. The system’s success in capturing accurate, real-time data during rain events demonstrates its potential for reducing the impact of disasters in densely populated urban settings, where sustainability and disaster resilience are key concerns.

A key advantage of the system is the modularity of its low-cost components, offering flexibility in selecting suitable elements to meet specific monitoring requirements. However, there is a need to balance the inclusion of additional sensors with maintaining data integrity. The correct placement of sensors is essential to obtain accurate information, and while low-cost sensors reduce upfront costs, they require ongoing maintenance, calibration, and testing. Regular calibration and field testing are necessary for environmental factors and sensor drift, ensuring the system's long-term reliability. Despite their limitations, low-cost sensors provide an efficient and scalable solution for disaster mitigation when adequately maintained.

Conclusions. A low-cost IoT-based monitoring system that includes an automatic water level recorder (AWLR) and an automatic weather station (AWS) for flood mitigation has been developed and tested. This system provides real-time river water level and meteorological data, enhancing flood forecasting and early warning capabilities. The prototype uses MaxBotix ultrasonic sensors for water level monitoring and PR-3001-GYL-N01 sensors to detect rainfall, with the ESP32 microcontroller serving as the CPU. The Wi-Fi and Bluetooth features of this microcontroller ensure smooth data exchange.

For the AWLR sensor used in flood prevention, a measurement gap of around 2 centimeters was detected, indicating excellent measurement performance by the sensor. Similarly, the rainfall and wind speed sensors in the AWS system demonstrated a reliability rate of 94.64 to 99.03%. In field tests in the Bekasi watershed, the system accurately recognized water level and weather changes, with only 1 second to 1 minute data transmission gaps. The system effectively recorded water level differences during rain events, such as November 4, 2023, showcasing its flood prediction capability. This real-time data visualization contributes to environmental knowledge and guides water resource management decisions and meteorological analysis. The web-based monitoring interface displays data from the AWLR and AWS, including river water level, air temperature, humidity, rainfall, air pressure, and wind speed.

This research contributes to sustainable urban environment management by developing a low-cost, scalable IoT-based water and weather monitoring system for disaster mitigation. The system integrates AWLR and AWS to provide real-time hydrometeorological data, supporting more effective flood forecasting and risk management in the Bekasi watershed. The system's low-cost design ensures its feasibility for broader implementation in other urban areas facing similar environmental challenges. It is a valuable tool for promoting disaster resilience in flood-prone regions.

This approach aligns with the goals of sustainable urban management by enhancing early warning systems and enabling timely responses to flood risks. It provides a proactive solution for protecting communities and infrastructure from the increasing threats posed by climate change and urbanization. The results of this study demonstrate that integrating real-time monitoring systems can significantly contribute to disaster preparedness, ensuring the sustainability of urban environments such as the Bekasi watershed area in facing hydrometeorological hazards.

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Conflict of interest. The authors declare that there is no conflict of interest.

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