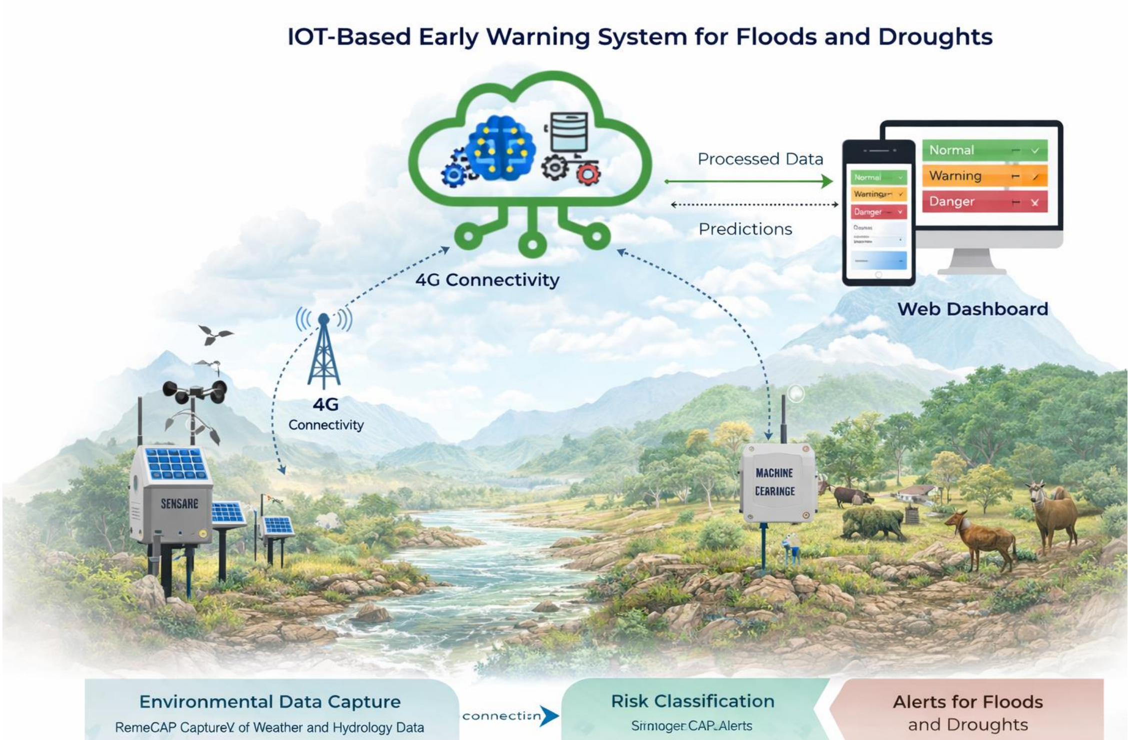
IoT-Based Early Warning System for Floods and Droughts



The IoT-Based Early Warning System for Floods and Droughts () is a deployed Internet of Things (IoT) solution designed to monitor hydrometeorological conditions in the Muvumba catchment in Rwanda and to provide early warnings about potential flood and drought events. The system connects distributed sensor nodes installed in the field, a cellular communication network, a cloud-based back end that performs data storage and prediction, and a web-based dashboard used by local authorities and communities. The overall goal is to continuously observe key environmental variables, analyze their evolution over time, and translate abnormal conditions into timely and actionable alerts.

EWS4FD relies on two main types of sensor nodes. The first type focuses on atmospheric and weather-related parameters. It integrates a Compact Weather Sensor (comprising seven sensors) as its primary sensing unit, combined with an embedded processing and communication module (the sensing device) and an integrated energy supply. The weather sensor measures variables such as air temperature, humidity, rainfall, wind speed, wind direction, barometric pressure, and light intensity, depending on the exact configuration. The embedded device acquires these raw signals, performs basic preprocessing (for example, unit conversion and range checking), and encodes the measurements into structured messages. This node operates autonomously in the field and is powered by a dedicated energy subsystem made of battery and solar panel, which allows it to run continuously without direct human intervention.

The second sensor node focuses on ground-level and hydrological conditions. It typically combines soil moisture with soil temperature sensors near rivers, channels, or other critical locations in the catchment and a water-level sensor installed in rivers. Similar to the weather node, this ground-focused node includes a local processing and communication unit that digitizes the readings, filters out obvious outliers, and packages the data for transmission. Both types of nodes are deployed at remote weather stations or monitoring sites within the Muvumba catchment. They are designed to operate independently and continuously, relying on their built-in power supply and robust enclosures to withstand outdoor environmental conditions.

For communication, EWS4FD uses a 4G cellular network to transfer data from the sensing devices to the cloud. Each node's sensing device acts as a gateway that periodically initiates a connection to the cellular network and uploads the latest batch of sensor readings. The nodes are configured with upload intervals that can be adjusted from the back end (for example, sending data every few minutes during the rainy season and less frequently during stable weather). Using 4G connectivity ensures that even stations in remote or hard-to-reach areas can provide near-real-time measurements without the need for wired infrastructure.

On the cloud side, EWS4FD provides a centralized platform that receives, validates, and stores all incoming sensor data. The back end maintains a time-stamped database of meteorological and hydrological observations for each weather station and sensor node. This historical archive is crucial for trend analysis and for training machine learning models. Once new data are ingested, the cloud platform performs integrity checks (for example, verifying that timestamps are consistent and values fall within plausible ranges) before inserting them into persistent storage. The platform also exposes programmatic interfaces that allow other services, such as forecasting modules or external tools, to query or retrieve the stored data.

The core decision logic of EWS4FD is implemented as cloud-based machine learning (ML) and analytics services. These services combine real-time measurements with historical records to estimate the likelihood of flood or drought conditions in different areas of the catchment. For instance, the ML models can correlate cumulative rainfall, soil moisture levels, river water height, and recent trends to forecast whether a river is approaching critical overflow thresholds or whether prolonged dry conditions may lead to drought. The prediction results are periodically recomputed as new data arrive, ensuring that the risk assessment reflects the most recent environmental state.

Based on the outcomes of these predictive models, the system automatically classifies the current situation for each monitored location into a small set of risk categories, such as Normal, Warning, or Danger. This classification is derived from predefined thresholds and domain-specific rules, for example, a combination of rainfall intensity, river level, and soil saturation. In the Normal state, the system logs the readings and updates the visualizations but does not raise any urgent alert. In the Warning state, the system flags the location as potentially at risk, prompting closer monitoring or preparatory actions. In the Danger state, the system indicates that conditions are likely to lead to flooding or severe drought if no intervention is taken, and the warning mechanisms are activated.

All sensor readings, prediction outputs, and risk classifications are exposed through a web-based dashboard. This dashboard acts as the main human interface of EWS4FD and is accessible to different stakeholders, such as local authorities, disaster management teams, and community representatives. Users can log into the dashboard to monitor current conditions at each station, inspect historical time series, and view risk maps or charts summarizing the situation across the catchment. The interface highlights stations in the Warning or Danger state and can display detailed information about their recent measurements and predicted evolution.

The dashboard also implements the early warning functionality itself. Depending on the risk classification, the system is able to trigger alerts, for example by sending notifications via email, SMS, or other communication channels configured for specific user groups. These alerts include the affected station or area, the type of risk (flood or drought), the current risk level, and, when applicable, recommended actions or guidance. In addition, authorized users can use the dashboard to remotely configure certain parameters on the sensor nodes, such as the data transmission interval. This closed loop from sensor configuration and data acquisition, through cloud-based analysis, to human-facing warnings and potential reconfiguration of the devices enables end-to-end operation of the system in a real environment.

From an end-to-end testing perspective, EWS4FD provides a concrete IoT deployment in which defects can occur at multiple layers. At the device level, bugs may affect sensor calibration, local preprocessing, power management, or transmission scheduling. In the communication layer, connectivity issues, packet loss, or misconfigured 4G parameters may delay or corrupt data. At the cloud level, problems in data validation, storage, or ML prediction logic may result in incorrect risk assessments. Finally, at the dashboard and alerting layer, faulty visualization, mislabelled risk states, or incorrect alert routing rules may prevent end users from receiving accurate and timely warnings. Because the system is deployed with real devices and real data streams, it is well suited for evaluating end-to-end testing strategies that aim to detect and diagnose faults across the entire IoT stack, from sensing in the field to decision making in the cloud and warning delivery to human users.