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A Municipal Flood Early-Warning Framework for Community-Centred Development in Urban Uganda

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Abstract
Urban flood early-warning services in Uganda face interconnected challenges involving incomplete rainfall records, limited monitoring infrastructure, intermittent power and communications, and fragmented arrangements for warning and response. Guided by the World Meteorological Organization's (WMO) people-centred early-warning framework and the Sendai Framework for Disaster-Risk Reduction, this paper develops a structured pre-deployment municipal framework linking risk knowledge, monitoring, communication, preparedness and accountable governance. The empirical component analyses daily Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) for Bwaise, Kalerwe and Mbarara, Uganda, for 2010–2024 and compares the two available Kampala-area series with ERA5 Ag precipitation estimates. Daily product-to-product correlations were 0.425 and 0.401; after monthly aggregation, they increased to 0.768 and 0.750. These results indicate temporal scale sensitivity but do not validate either product against ground rainfall. The weaker daily agreement supports a design in which gridded products provide historical context rather than serving as sole operational triggers: locally installed rain gauges and, where appropriate, water-level sensors are proposed to supply site-specific observations, subject to calibration and field evaluation. The framework was developed through an applied design-synthesis process that mapped the rainfall findings, documented resilient monitoring requirements and published governance and participation literature onto a nine-stage warning-service lifecycle. It specifies proposed responsibilities, resilient data handling, community participation procedures and indicators of readiness, continuity and usefulness. The resulting contribution is a structured planning resource for municipal adaptation and pilot design; field validation, stakeholder testing and local cost assessment remain necessary before operational adoption.

Introduction

Flooding presents a persistent challenge to urban development, public infrastructure, livelihoods and community safety in Ugandan cities. Its consequences are particularly serious in densely settled and low-lying urban and peri-urban environments where drainage constraints, land-use change, settlement patterns and inadequate environmental information can increase exposure. In Kampala,

flood-management involves multiple institutional and community actors, yet persistent flooding has exposed difficulties in coordinating interventions and reconciling different forms of flood-risk knowledge (Arinabo, 2023; Chereni et al., 2020). This study therefore confines its empirical claims to the Ugandan locations analysed; references to evidence from other African countries are used comparatively, not as proof that conditions are uniform across the region.

The practical value of flood early-warning depends on more than the availability of forecasting algorithms, sensors or digital dashboards. Warning services must connect risk knowledge, monitoring, communication and preparedness to respond. These four elements are central to the people-centred approach promoted by the World Meteorological Organisation (WMO, 2018). The Sendai Framework for Disaster-Risk Reduction similarly emphasizes understanding disaster-risk, strengthening risk governance, investing in resilience and enhancing preparedness for effective response (United Nations Office for Disaster-Risk Reduction [UNDRR], 2015). Together, these frameworks provide the conceptual foundation for treating early-warning as a socio-technical public service: monitoring technology generates evidence, while institutions and communities interpret, communicate and act on it.

However, the institutional and technical conditions required to deliver these functions are not always present at municipal level. Historical rain-gauge records may be incomplete or difficult to access. Monitoring equipment may experience power interruptions, network outages, sensor drift or physical damage. Municipal authorities may have limited technical personnel and recurring maintenance budgets. Communities may also receive warnings through channels that are inaccessible, unfamiliar or not trusted. These constraints make it necessary to assess not only whether monitoring data are generated, but whether the complete service can remain available, communicate reliably and be useful to intended recipients. Operational indicators are therefore needed to establish a baseline, identify service failure and guide improvement before expansion.

Evidence from Uganda illustrates these difficulties. Canwat (2025) examined a community-based transboundary flood early-warning arrangement in Elegu, Northern Uganda, and identified the importance of local relationships and locally available resources in sustaining warning activities, alongside limitations in night-time monitoring and communication. Although Elegu is a rural, transboundary riverine setting rather than a dense urban drainage environment, the transferable lesson for Kampala is institutional and procedural: locally trusted networks can help observe, relay and act on warnings when formal monitoring is constrained. The specific flood mechanisms and thresholds, however, must be established for each urban catchment. In Kampala, Chereni et al. (2020) demonstrated that changes in institutional responsibilities can influence flood-mitigation arrangements, while Arinabo (2023) highlighted the importance of reconciling institutional practices with different forms of urban flood-risk knowledge. These findings indicate that technical monitoring and institutional arrangements must be considered together.

Comparable African evidence reinforces this argument. Atanga (2020) found that flood-prone community leaders in Accra were involved mainly during implementation rather than the earlier stages of flood-risk strategy-making. In Namibia, Moises et al. (2024) identified institutional bureaucracy, inadequate capacity and funding as constraints affecting flood-warning coordination. Muhame et al. (2024) also emphasized the role of community participation and locally appropriate information dissemination channels in disaster-risk reduction.

Although these studies provide important insights, municipal authorities still require guidance for connecting rainfall information, local monitoring infrastructure, data validation, institutional decision-making and community response within a coherent service arrangement. This paper

addresses that need through an applied design-synthesis based on the study's rainfall-product analysis, technical design principles for resilient low-cost IoT monitoring, the WMO and Sendai frameworks, and published research on flood governance and community participation. No new IoT field deployment, hardware experiment, stakeholder interview or participatory field exercise is claimed in this paper. The IoT elements are presented as proposed design requirements to be assessed during a future municipal pilot.

Background and conceptual grounding

People-centred early-warning systems

An early-warning system is not simply a mechanism for detecting a hazard. It is an arrangement of capacities that enables information about a potential hazard to be generated, communicated and translated into protective action. The WMO (2018) identifies four interrelated elements: disaster-risk knowledge; detection, monitoring, analysis and forecasting; dissemination and communication; and preparedness to respond.

The four elements provide a useful foundation for municipal implementation. Risk knowledge identifies exposed locations, vulnerable populations and the characteristics of previous flood events. Monitoring and forecasting generate information about changing environmental conditions. Communication delivers authoritative and actionable warnings to the intended recipients. Preparedness establishes the responsibilities and actions needed before, during and after an event.

The Sendai Framework places these activities within a wider disaster-risk governance agenda. Its priorities include understanding risk, strengthening disaster-risk governance, investing in resilience and enhancing preparedness for effective response (UNDRR, 2015). For municipalities, this implies that warning services should be integrated into development planning, environmental management, community engagement and local emergency-response arrangements. The proposed framework therefore treats early-warning as a municipal public service supported by technical infrastructure, institutional coordination and community participation.

Flood governance and institutional coordination in African municipalities

Urban flood-management involves multiple actors whose responsibilities may overlap. These include local government, drainage and water authorities, disaster-management agencies, environmental departments, community organisations and national meteorological institutions. Research in Kampala demonstrates why coordination matters. Chereni et al. (2020), using Bwaise III as a case study, examined the influence of governance rearrangements on flood-risk management. Their findings show that changes in institutional roles and responsibilities can influence the implementation of flood-mitigation measures. Arinabo (2023) further demonstrates that flood-management interventions can be weakened when institutional priorities, political influences and the knowledge of different urban actors are not adequately reconciled.

A related institutional challenge was identified in Namibia. Moises et al. (2024) found that bureaucratic arrangements, limited institutional capacity, inadequate funding and emphasis on post-disaster response can undermine the effectiveness of flood-warning arrangements. These findings suggest that municipalities need explicit procedures for assigning responsibility for observation verification, warning authorisation, communication, incident recording and maintenance. A technical platform should support these institutional responsibilities rather than operate independently of them.

Community participation and local knowledge

Communities are not merely recipients of warnings. Residents may possess detailed knowledge of local flood pathways, drainage blockages, water-level changes, historical inundation and locations where particular communication channels are effective. Canwat (2025) provides relevant evidence from Elegu Town Council in Northern Uganda. The study documents how upstream and downstream relationships, kinship and locally available resources contributed to community-based transboundary warning arrangements. It also identifies limitations associated with inadequate government support and the absence of night-time monitoring and communication.

In Accra, Atanga (2020) found that community leaders from flood-prone areas participated mainly during implementation rather than in the development of flood-risk management strategies. This distinction is important because participation limited to the dissemination stage may exclude residents from decisions about monitoring locations, warning thresholds and response priorities. In South Africa, Muhame et al. (2024) found that community volunteers and ward committee members played important roles in disaster-preparedness activities. Their study also identified churches, schools, mobile messaging and community communication channels as relevant means of disseminating warning information.

The implication for the proposed framework is that community participation should begin during site assessment and continue through system design, communication testing, operational review and evaluation. Community observations should complement instrument data, with their location, time and source recorded so that their reliability can be assessed.

Rainfall information and uncertainty in data-scarce settings

Satellite and reanalysis rainfall products provide valuable information where ground observations are sparse. CHIRPS combines satellite-derived information with station observations to provide a long-term precipitation record suitable for regional and local environmental analysis (Funk et al., 2015). However, the availability of a long rainfall record does not guarantee that its estimates are sufficiently accurate for every local decision. Dinku et al. (2018) evaluated CHIRP and CHIRPS across eastern Africa using approximately 1,200 rain-gauge stations and demonstrated that performance varies across geographical locations and temporal scales. Their findings also identified weaker performance in some coastal and mountainous areas.

Macharia et al. (2022), using observations from 596 TAHMO stations across Africa, further demonstrated that satellite-derived rainfall products have important differences in bias and event detection performance. Their analysis showed that product performance varies across geographical regions and temporal aggregation levels. Consequently, rainfall products should be evaluated according to the intended application rather than assumed to be interchangeable.

ERA5 provides a global atmospheric and land-surface reanalysis and can serve as an additional source of historical environmental information (Hersbach et al., 2020). Nevertheless, reanalysis estimates should also be interpreted according to their spatial and temporal characteristics and should not automatically be treated as local ground observations.

For municipal flood-warning purposes, historical gridded rainfall can support preliminary characterisation, seasonal analysis and initial system configuration. Operational thresholds for daily rainfall or accumulated precipitation should, where possible, be evaluated against local rain-gauge observations and independently documented flood events.

Methodology

Research approach

The paper employed an applied design-synthesis approach informed by the underlying rainfall-data analysis, technical requirements reported in the resilient IoT and monitoring literature, and published research on flood governance, community participation and early-warning coordination. It did not involve new hardware testing, a municipal deployment, interviews or participatory fieldwork. The purpose was to translate the available empirical and documentary evidence into a structured municipal planning framework. The design process was organized around nine linked stages of a municipal warning-service: (1) site assessment and stakeholder preparation; (2) data-source selection and management; (3) sensor and communication installation; (4) data-quality management; (5) risk interpretation and alert configuration; (6) warning authorization; (7) community communication and action; (8) response and incident recording; and (9) operations, maintenance and service review.

The synthesis was informed by three evidence categories:

1. Empirical rainfall-product comparisons undertaken in the underlying research, used to identify the implications of temporal aggregation and the limits of gridded rainfall agreement.
2. Technical requirements for low-cost, resilient IoT monitoring and data-quality management, treated as proposed design criteria rather than results of a field-tested prototype.
3. Published research and established frameworks on flood governance, community participation and early-warning coordination in Uganda and other African settings.

The synthesis followed a traceable mapping logic. Rainfall evidence informed data-source selection, uncertainty recording and the recommendation that local observations should complement gridded products for short-timescale decisions. Monitoring requirements informed sensor siting, backup power, local buffering, time-stamping, fault detection and maintenance stages. The WMO four-element model organised the service functions, while the Sendai priorities informed risk governance, institutional accountability and preparedness. Governance and participation studies informed role allocation, inclusive communication, feedback and conflict-resolution procedures. These elements were then arranged in the sequence needed to move from site readiness to sustained municipal service operation. The paper distinguishes measured findings, literature-derived design principles and proposed procedures requiring pilot evaluation.

Rainfall-data evidence

The underlying rainfall analysis assembled daily CHIRPS precipitation records for Bwaise, Kalerwe and Mbarara, Uganda, covering 2010–2024, with 5,479 observations for each location. The CHIRPS series therefore provide the three-location descriptive rainfall dataset. The matched ERA5 Ag comparison archive contained only two Kampala-area precipitation series and did not contain a corresponding Mbarara series for the same analysis. Mbarara is consequently a CHIRPS-only location in this study and does not contribute to the reported CHIRPS–ERA5 Ag correlations. The available manuscript records the absence of a matched ERA5 Ag series but does not establish a further reason for that data availability gap. No synchronised ground-gauge comparison was available for any of the reported product-to-product correlations.

The reported daily correlations between the available rainfall products were 0.425 and 0.401. After monthly aggregation, the corresponding correlations increased to 0.768 and 0.750. These results were used to examine how the relationship between the rainfall products changed with temporal aggregation. They were not interpreted as evidence that either product accurately represented ground rainfall because a complete synchronised ground-gauge reference was unavailable.

The analysis therefore informed the framework's recommendation that rainfall products should be assessed at the temporal scale relevant to the intended municipal decision.

Framework synthesis

The proposed implementation stages were developed by systematically connecting the three evidence categories to the operational functions of a municipal warning-service. The WMO's (2018) four-element framework provided the functional structure: risk knowledge; detection, monitoring, analysis and forecasting; dissemination and communication; and preparedness to respond. The Sendai Framework (UNDRR, 2015) informed the emphasis on understanding risk, governance, investment in resilience and preparedness. The rainfall findings informed data selection and uncertainty controls; resilient monitoring requirements informed acquisition, buffering, power continuity and maintenance; and published studies informed institutional coordination, participation and communication procedures (Arinabo, 2023; Atanga, 2020; Canwat, 2025; Chereni et al., 2020; Moises et al., 2024; Muhame et al., 2024).

The paper does not report a completed municipal deployment, a controlled trial involving municipal emergency-response teams or an evaluation of community warning outcomes. The proposed stages, responsibilities and indicators are therefore implementation recommendations rather than experimentally validated municipal procedures.

Findings: proposed municipal flood early-warning deployment framework

Site assessment and stakeholder preparation

Implementation should begin with identifying flood-prone locations, drainage pathways, water-level observation points, critical infrastructure and communities requiring warning services. The site assessment should combine historical flood reports, community knowledge, drainage and river information, elevation and land cover data, historical rainfall, existing monitoring stations, communication coverage and power availability.

The importance of integrating local knowledge with institutional information is supported by Kampala's flood-management research, which identifies the need to reconcile different forms of risk knowledge and institutional responses (Arinabo, 2023). A site assessment should therefore include a documented community mapping exercise during which residents identify previous flood extents, drainage blockages, locally observed water-level changes, vulnerable facilities and locations where warnings are difficult to receive. The municipality should record the date, location, source and type of each observation and compare it with available maps, monitoring records and other reports. A site register should document each proposed monitoring point, its coordinates, reason for selection, access arrangements, responsible institution and maintenance contact.

Before installation, the municipality should establish a coordination group comprising a disaster-management focal person, an environmental or water-resource officer, a technical system operator, community representatives (including groups likely to face communication barriers), an authorised warning-issuing institution and, where appropriate, a meteorological or hydrological specialist. Participation should begin with site-selection and continue through message design, communication testing, incident review and periodic service evaluation. Meeting records should capture issues raised, decisions, responsible persons and follow-up dates. The municipality should document each participant's responsibilities and establish an escalation route for unresolved technical, institutional and community concerns.

Data-source selection and integration

The municipality should assess the strengths and limitations of each available data-source rather than rely on a single source without qualification.

CHIRPS and other suitable rainfall products can support historical characterisation, preliminary site assessment and initial system configuration where local rain-gauge records are incomplete. Their spatial coverage, temporal resolution, extraction method and known limitations should be documented. Regional validation research demonstrates that performance varies across locations and temporal scales (Dinku et al., 2018; Macharia et al., 2022). Low-cost rain gauges can provide localised measurements. Their usefulness depends on suitable siting, inspection, calibration and maintenance. Where appropriate, water-level observations can provide information closer to the conditions associated with local inundation. Installation should consider mounting, debris, vandalism, sensor range and safe maintenance access.

Structured reports from residents and local responders can complement instrument data. Reports should include location, time, observation type and a means of assessing reliability. Elevation, drainage, land cover and infrastructure data can help interpret where rainfall may translate into localised impacts. A data register should identify each source's provider, spatial coverage, resolution, update frequency, known limitations and responsible custodian. It should distinguish direct measurements from gridded estimates, forecasts, community reports and imputed values. Because power and connectivity are potential points of failure, site-selection must also assess mains reliability, solar exposure, cellular or other available network coverage, safe equipment access and the feasibility of local data storage and alternative warning channels.

Sensor and communication installation

The initial installation should use a limited number of rainfall and water-level monitoring points selected through the site assessment. The number of devices should be determined by monitoring objectives, spatial coverage, available budget and maintenance capacity. Each installation should document the sensor model and device identifier, geographical coordinates and installation height, measurement variable and unit, expected reporting interval, power source and backup arrangement, communication method, calibration and maintenance schedule, and responsible technician or service provider.

Where mains power is unreliable, the design should provide appropriately sized battery backup and, where feasible, a solar charging arrangement; the autonomy requirement should be set from the intended reporting interval, local outage patterns and maintenance capacity rather than assumed universally. Where cellular connectivity is intermittent, devices or edge gateways should store observations locally with timestamps and automatically synchronise them when a connection returns. Communication design should use available redundant paths where feasible (for example, cellular plus a locally supported radio/LoRa link), while recognising that LoRa requires compatible local infrastructure and does not itself provide internet backhaul. The system should monitor battery state, last successful transmission and device health.

Each record should preserve both the measurement time and the time it was received by the central service. This distinction enables delayed observations to be identified and prevents old measurements from being interpreted as current conditions. During a network outage, locally buffered observations should be marked as delayed on synchronisation and must not be displayed as current. During a power interruption, the device should enter a documented low-power or shutdown state and resume collection and synchronisation when power is restored; critical sites should have a locally agreed manual observation procedure. If digital channels fail, warning dissemination should fall back to pre-

agreed community focal persons, radio, sirens or public-address systems as locally appropriate. The installation plan should identify procedures for sensor replacement, communication failure and loss of power.

Data-quality management

Data-quality checks should be applied before observations are used for risk interpretation, covering required fields, valid formats, plausible physical ranges, measurement and receive timestamps, duplicate observations, missing reporting intervals, sensor status, communication health and abrupt changes that require further review. Automated, real-time quality-control flags should be distinguished from asynchronous post-event quality audits. A suspicious extreme value should be flagged for rapid verification, but a potentially dangerous observation should not be silently discarded: the operating procedure should permit precautionary escalation while verification proceeds. Any corrected or imputed values should remain identifiable as estimates rather than being presented as direct sensor measurements.

A data-quality log should document rejected observations, warnings, missing intervals, sensor outages and corrective actions to support troubleshooting, auditability and accountability. The service should also distinguish between a missing report and a confirmed sensor failure, since a missed reporting interval may result from a sensor problem, power interruption, network failure or temporary communication delay; the responsible operator should therefore investigate before assigning a definitive cause. This approach is consistent with the broader requirement to connect monitoring information with risk analysis and authoritative warning communication (WMO, 2018).

Risk interpretation and alert configuration

Rainfall thresholds should not be transferred from one municipality to another without local assessment. Threshold selection should consider local rainfall characteristics, drainage conditions, flood history, topography, water-level observations and the warning lead time required by communities and responders.

A transparent rule-based approach may be appropriate for an initial monitoring service. More complex predictive models should be introduced only when sufficient quality-controlled observations and independently documented flood-event labels are available.

A warning decision should consider:

- Observed or forecast rainfall conditions.
- The period over which rainfall has accumulated.
- Water-level observations where available.
- Data completeness and confidence.
- The location and likely exposure.
- The operational status of sensors and communication services.

The service should distinguish a high-risk assessment supported by reliable observations from a potentially high-risk situation in which data-quality is poor. Low confidence should trigger verification and an appropriate precautionary procedure rather than silently suppressing a warning.

This distinction is important because warning communication must convey authoritative and actionable information, including relevant uncertainty, rather than simply display a model-generated risk category (WMO, 2018). Warning categories, thresholds and decision authority must be documented and approved locally before operational use.

Warning communication and community action

A warning should identify the affected area, hazard, expected time window, recommended action and issuing authority. Messages should use locally understood language and avoid unnecessary technical terminology.

The municipality should define who verifies observations, who authorises official warnings, which communities and institutions receive each warning level, which communication channels are used, what action recipients should take and how delivery and response are recorded.

Potential channels include SMS, mobile messaging, radio, community focal persons, sirens, public-address systems, schools and local community institutions. The selected combination should reflect local access, language, network availability and the needs of people who may be less likely to receive digital messages.

Research in South Africa demonstrates that community volunteers, ward structures and locally preferred communication channels can play important roles in disaster-risk information dissemination (Muhame et al., 2024). Evidence from Accra also indicates that community leaders should participate in the development of flood-risk strategies rather than only in their implementation (Atanga, 2020).

Community engagement should take place before operational launch. Residents should be able to report inaccurate locations, unclear messages, missed alerts and changes in local flood conditions through accessible channels. Feedback should be logged, acknowledged and assigned to a responsible officer, with the action taken or reason for non-action recorded. Community feedback should inform subsequent revisions to warning content, delivery channels and operating procedures.

Operations, maintenance and service accountability

A municipal monitoring service requires recurring operational tasks. These should be assigned to named roles and supported by an appropriate budget.

Table 1. Operational Activities, Responsible Roles and Records for Municipal Flood Early-Warning Service Management.

Operational activity	**Responsible role**	**Suggested record**
Sensor inspection	Field technician	Inspection log
Calibration and cleaning	Technical team	Calibration record
Data-quality review	Data operator	Quality report
Sensor outage follow-up	System operator	Incident record
Warning authorisation	Designated municipal officer	Warning decision log
Community feedback	Community focal person	Feedback register
Monthly service review	Municipal coordination group	Performance report

The municipality should define escalation procedures for equipment failure, communication loss, missing data and suspected false readings.

Institutional coordination and funding arrangements are essential to sustaining warning services. Moises et al. (2024) identified institutional capacity, bureaucracy and inadequate funding as important constraints in flood-warning implementation in Namibia. The proposed framework therefore treats maintenance, staff responsibility and operational budgeting as core implementation requirements rather than optional activities.

A service should not be expanded simply because additional devices can be purchased. Expansion should depend on the municipality's demonstrated capacity to operate, maintain and govern the existing service.

Phased implementation model

The proposed implementation model consists of four phases, beginning with readiness and baseline assessment, followed by the establishment of a minimum viable monitoring service, a controlled operational pilot, and eventual institutional expansion.

Phase 1: Readiness and baseline assessment

The first phase focuses on establishing the institutional, technical and community foundations required for implementation. This involves identifying priority communities and monitoring sites, collecting historical rainfall and flood records, and mapping existing infrastructure and communication coverage. Institutional responsibilities are identified to clarify the roles of the different stakeholders involved in flood monitoring, warning dissemination and response. A risk and data-source register is also prepared to document potential hazards, available information sources and relevant data limitations. In addition, community representatives are consulted to understand local flood experiences, existing coping mechanisms and warning needs. The expected outputs of this phase include a site assessment report, data inventory, stakeholder and responsibility matrix, preliminary operating procedure and initial community communication assessment.

Phase 2: Minimum viable monitoring service

The second phase involves establishing a basic but functional monitoring service using a limited number of selected sensors. The activities include installing the sensors, configuring observation collection and local data buffering, and implementing procedures for data validation and monitoring. A basic dashboard and incident log are developed to support the visualisation and documentation of incoming observations and system events. Warning communication is tested with a small group of intended users to assess whether information can be disseminated and understood effectively. Equipment requirements, connectivity arrangements and maintenance needs are also documented to support continued operation. The expected outputs include a working monitoring prototype, sensor register, data-quality report, tested warning communication procedure and preliminary maintenance plan.

Phase 3: Controlled operational pilot

The third phase involves operating the monitoring service over a defined observation period to assess its technical and operational suitability. Sensor observations are compared with available independent reference data, while fault simulations and communication-outage tests are conducted to examine the system's ability to handle disruptions. The implementation team records alert delivery and response activities and obtains feedback from community members and institutional users. Warning authorisation and escalation procedures are also assessed to establish whether responsibilities and decision-making processes are sufficiently clear. The expected outputs include a pilot evaluation report, revised operating procedures, documented system limitations, a cost and maintenance assessment, and a stakeholder feedback report.

Phase 4: Institutional expansion

The final phase focuses on extending the service and embedding it within municipal operations, subject to a review of the pilot's performance and identified limitations. Expansion may involve integrating additional monitoring points, formalising technical support and procurement arrangements, and training municipal and community personnel. Recurring performance assessments and governance reviews are established to support accountability, maintenance and

continuous improvement. The service is also incorporated into relevant municipal development and disaster-risk management plans to strengthen institutional ownership and long-term sustainability. The expected outputs include a municipal operating plan, maintenance and replacement budget, training materials, a scale-up decision and implementation schedule, and formalised institutional responsibility and reporting arrangements.

Proposed operational performance indicators

The following indicators are proposed for municipal monitoring. They are not universal targets; baseline values and locally appropriate targets should be agreed before implementation.

Table 2. Proposed Operational Performance Indicators for Assessing Municipal Flood Early-Warning Service Readiness, Continuity and Usefulness.

Dimension	Indicator	Operational purpose
Data availability	Percentage of expected observations received	Identifies monitoring gaps
Data-quality	Percentage of records passing validation	Tracks observation usability
Sensor reliability	Number and duration of sensor outages	Supports maintenance planning
Timeliness	Time from measurement to central availability	Identifies communication delay
Warning performance	Time from decision to message dispatch	Assesses the warning workflow
Communication	Percentage of intended recipients reached	Assesses dissemination
Community response	Recorded acknowledgement or action	Assesses practical usefulness
Maintenance	Time to restore failed monitoring points	Assesses operational support
Financial sustainability	Annual operating cost per monitoring site	Supports budgeting

Performance reports should state the measurement period, denominator, data-source and missing information. A high availability percentage should not be reported without explaining how planned maintenance and communication outages were treated.

These indicators extend the technical monitoring perspective to include institutional performance and community usefulness. This is consistent with the WMO's (2018) emphasis on communication and preparedness and the Sendai Framework's (UNDRR, 2015) focus on governance and resilience.

Implementation risks and mitigation

Table 3: Implementation Risks, Potential Consequences and Proposed Mitigation Measures for the Municipal Flood Early-Warning Framework

Risk	Possible consequence	Proposed mitigation
Inaccurate or incomplete rainfall-data	Misleading risk interpretation	Multi-source comparison and local validation
Sensor damage or drift	Unreliable measurements	Inspection, calibration and replacement plan
Network interruption	Delayed information and warnings	Local buffering and alternative communication
Unclear warning authority	Delayed or conflicting messages	Formal authorisation and escalation procedure
Community distrust	Low response to warnings	Participatory design and transparent communication
Insufficient maintenance funding	Loss of service after a pilot	Recurring budget and assigned technical responsibility
False or missed alerts	Reduced trust and increased exposure	Independent evaluation and threshold review
Limited institutional coordination	Fragmented response	Formal coordination arrangements and shared operating procedures

The risks reflect challenges identified in African flood-management studies, including institutional fragmentation, limited local capacity, insufficient resources and weak community involvement (Arinabo, 2023; Atanga, 2020; Moises et al., 2024).

Discussion

Rainfall-data agreement and municipal decision-making

The rainfall comparison provides an empirical illustration of why data-source selection should be linked to the intended decision. The available daily correlations between CHIRPS and ERA5 Ag were 0.425 and 0.401, increasing to 0.768 and 0.750 after monthly aggregation.

The stronger monthly association indicates that the relationship between the products changed with temporal aggregation. It does not establish that either product accurately represented ground rainfall, because a complete synchronised rain-gauge reference was unavailable.

This limitation is important in the context of regional rainfall-product research. Dinku et al. (2018) demonstrated spatial and temporal variability in CHIRPS performance across eastern Africa, while Macharia et al. (2022) found differences in bias and rainfall-event detection among satellite-derived products. Municipalities should therefore avoid assuming that a product suitable for historical monthly characterisation is automatically suitable for daily operational warning thresholds.

The proposed framework recommends using historical gridded rainfall for preliminary characterisation and system configuration while requiring local validation for operational decisions. This is a more defensible approach than presenting gridded estimates as substitutes for ground observations.

Development administration and institutional coordination

The framework positions early-warning as a municipal service requiring coordination across technical, administrative and community functions.

The Kampala studies demonstrate that flood-management outcomes are shaped by the interaction of institutional responsibilities, urban actors and different forms of risk knowledge (Arinabo, 2023; Chereni et al., 2020). The Namibia study similarly identifies coordination and institutional capacity as important requirements for effective warning implementation (Moises et al., 2024).

These findings support the need for clearly documented responsibility for data verification, warning authorisation, communication and maintenance. A warning decision should be traceable to its supporting observations, confidence assessment, authorising officer and communication record.

This institutional dimension is central to the proposed framework's contribution to development administration. It translates the technical requirements of monitoring into identifiable municipal functions that can be assigned, budgeted and reviewed.

Community participation and the usefulness of warnings

Community participation should not be treated only as a final stage in message dissemination. Residents can contribute flood histories, identify vulnerable locations, report observed conditions, assess message clarity and provide feedback on whether warnings reach intended recipients.

Community participation should not be treated only as a final stage in message dissemination. Residents can contribute flood histories, identify vulnerable locations, report observed conditions, assess message clarity and provide feedback on whether warnings reach intended recipients. For the proposed service, participation is operationalised through community mapping, representation in site-selection and coordination meetings, review of draft warning messages, practical communication

tests and a feedback register. These procedures convert the general principle of inclusion into documented tasks, assigned roles and reviewable outputs.

The framework recommends a documented procedure for reconciling community observations and instrument-based assessments when they diverge. First, the report should be logged with its location, time, source and description; second, the technical operator should check sensor status, timestamps, nearby observations, rainfall information and possible communication delays; third, the community focal person should seek clarification from the reporting residents or local responders where safe and appropriate. The coordination group should review unresolved discrepancies and record whether they reflect different spatial coverage, timing, local drainage conditions, sensor malfunction or uncertainty in the community report. The designated public authority retains responsibility for authorising official warnings. Where credible local reports indicate immediate danger despite a below-threshold sensor reading, the procedure should allow precautionary escalation and rapid verification rather than dismissing the report. Decisions, evidence considered, dissenting views and follow-up actions should be recorded transparently. This process treats community knowledge as evidence to be examined alongside technical data, not as a substitute for formal warning authority.

Phased implementation and service sustainability

The four-phase model addresses the risk of procuring a large sensor network before a municipality has established the capacity to operate and maintain it.

A limited monitoring service can expose practical requirements relating to data-quality, connectivity, warning authority, staff training and maintenance. These lessons can inform a scale-up decision.

The proposed performance indicators also connect technical operation with public service outcomes. Data availability and sensor reliability are important, but they should be considered alongside warning dispatch, recipient reach, community response and operating costs.

The framework therefore encourages municipalities to evaluate both technical continuity and the usefulness of the service to communities. It also recognises that implementation depends on local resources and institutional capacity, not merely on the availability of technology.

Contribution to municipal development practice

The principal contribution of this paper is an integrated municipal deployment sequence that connects rainfall-data interpretation, resilient monitoring, institutional governance and community response.

The framework provides three practical contributions.

First, it offers a data-conscious approach for municipalities that cannot immediately establish dense rain-gauge networks. Historical gridded rainfall can support initial analysis, but the framework requires its limitations to be recorded and operational thresholds to be locally assessed. Second, it translates monitoring functions into administrative responsibilities. This includes assigning responsibility for data-quality review, warning authorisation, communication, incident management and maintenance. Third, it embeds community participation throughout the service lifecycle rather than treating residents only as recipients of warnings.

The framework is designed first for municipal application in Uganda. Its principles may be considered elsewhere, including other East African cities, but transfer requires local assessment rather than direct replication. Minimum prerequisites include a clearly designated legal or administrative authority for issuing warnings; an identified municipal unit responsible for operating and maintaining the service; access to at least one viable communication route between monitoring points and the coordinating institution, or a locally managed alternative; arrangements for community-level dissemination during

network failure; trained personnel; and a recurring operations-and-maintenance budget. Sensor type, network technology, warning thresholds, institutional mandates and community channels must be adapted to local flood mechanisms and governance arrangements.

Limitations

This paper presents a structured pre-deployment framework informed by historical rainfall analysis, technical design requirements for resilient monitoring and published research on governance and participation. It does not report a completed municipal deployment, a controlled evaluation involving municipal emergency-response teams, new IoT hardware testing or primary stakeholder fieldwork.

The rainfall comparison was limited to two Kampala-area ERA5 Ag series and did not include a corresponding comparison for Mbarara. Mbarara was included in the CHIRPS series for historical geographical characterisation, but a matched ERA5 Ag series was not available in the comparative archive. A complete synchronised ground-gauge reference was not available. Consequently, the reported correlations describe agreement between gridded products and should not be interpreted as validation of rainfall accuracy.

The proposed alert-management procedures, institutional roles, community participation arrangements and performance indicators have not yet been evaluated through a municipal operational pilot. The paper does not establish locally validated flood-warning thresholds, warning lead times, community response rates, sensor reliability under local operating conditions or the financial viability of a specific deployment.

Further field research is required to assess sensor performance, communication reliability, warning delivery, community response, institutional adoption and recurring operating costs.

Recommendations and implications

Based on the proposed framework and rainfall analysis, several actions are recommended. Municipal authorities should begin with a documented readiness assessment and establish clear responsibilities for data management, warning authorisation, communication and maintenance. Environmental and technical teams should document data provenance and uncertainty, validate local thresholds, and distinguish measured observations from estimates and community reports. Community organisations and local leaders should participate in site assessments, warning-message design, communication testing and feedback processes. Development partners and research institutions should support controlled municipal pilot projects to evaluate sensor reliability, warning delivery, community response and recurring operational costs. Finally, future research should test the framework through field deployments in different East African municipal settings and assess its institutional, technical, financial and community outcomes.

Conclusion

This paper presents a structured pre-deployment framework for connecting rainfall information and resilient monitoring with municipal flood early-warning operations in urban Uganda. Its conceptual foundation combines the WMO people-centred early-warning framework with the Sendai Framework, positioning early-warning as a public service that links risk knowledge, monitoring, communication, preparedness and accountable governance. The empirical rainfall analysis found that daily CHIRPS–ERA5 Ag product correlations for the two available Kampala-area comparisons were 0.425 and 0.401, rising to 0.768 and 0.750 after monthly aggregation. These product-to-product relationships demonstrate sensitivity to temporal scale; they do not establish ground-level accuracy. The results therefore support using gridded rainfall for historical characterisation while requiring locally observed and validated information for operational short-timescale decisions.

The framework's contribution is an explicit nine-stage municipal service lifecycle that connects data-source selection and uncertainty management with resilient sensor operation, risk interpretation, warning authorisation, community communication, response recording and maintenance. It also proposes operational indicators covering data availability and quality, sensor outages, reporting and warning timeliness, recipient reach, community acknowledgement or action, restoration time and operating cost. Community participation is specified through mapping, representation in planning, message review, communication testing and logged feedback. Where community observations conflict with sensor thresholds, the proposed procedure requires documentation, technical checking, community clarification, transparent review and precautionary escalation where credible immediate danger is reported, while retaining formal warning authority with the designated institution. These are proposed procedures, not validated outcomes. The framework's scholarly and administrative contribution is to make the technical, institutional and community requirements of a municipal warning-service explicit and assessable before procurement or scale-up. Pilot deployment, stakeholder assessment, threshold validation and local cost analysis are the next steps needed to establish operational performance.

Declarations

Author contributions: Muwanga Erasto Kosea[1], conceptualisation, methodology, data curation, formal analysis, investigation, writing of the original draft, review and editing, Dr Otanga Daniel[2] review and supervision, Dr. Satwinder Singh Rupra[3] review and supervision.

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval and consent: This study involved the analysis of rainfall datasets and the development of a proposed municipal flood early-warning implementation framework. It did not involve direct experimentation with human participants.

Data availability: The rainfall-data analysed in this study were obtained from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) and the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis datasets.

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