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Review

Common Alerting Protocol (CAP) for Flash Flood Early Warning Systems: A Global Review of Implementations, Technical Approaches, and Operational Challenges

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Abstract

Flash floods represent one of the most lethal natural hazards globally, requiring rapid, accurate, and geographically precise warning systems to protect vulnerable populations. The Common Alerting Protocol (CAP), standardized by OASIS and endorsed by the International Telecommunication Union (ITU) as Recommendation X.1303, provides a machine-readable, channel-agnostic framework for emergency alerting. This paper presents a comprehensive review of CAP implementations for flash flood early warning systems worldwide, synthesizing evidence from 30 peer-reviewed publications, technical standards, and operational case studies. We systematically analyze area delimitation methodologies (geocodes, polygons, hybrid approaches), document operational implementations across 10 countries spanning Asia, North America, Europe, and Africa, and evaluate technical architectures, dissemination channels, and performance characteristics. Key findings reveal that successful implementations employ diverse area delimitation strategies tailored to local geographic information infrastructure, with geocode-based administrative targeting (FIPS, HASC, NUTS, SALB) and polygon-based coordinate delimitation representing the dominant approaches. Operational systems demonstrate multi-channel dissemination capabilities (SMS, cell broadcast, satellite radio, web platforms, broadcasting) and sophisticated automation enabling sub-minute warning latency. However, significant challenges persist, including geocoding standardization gaps, message optimization for bandwidth-constrained channels, institutional coordination complexity, and limited evidence from resource-constrained contexts. This review identifies critical research priorities including flash flood-specific performance evaluation, low-resource context adaptations, geocoding harmonization, and long-term sustainability assessment. The findings provide evidence-based guidance for policymakers, emergency managers, and researchers considering CAP adoption for flash flood warning applications.

Keywords: common alerting protocol; flash floods; early warning systems; emergency alerting; disaster management; geographic information systems; multi-channel dissemination; interoperability

1. Introduction

1.1. Flash Floods as a Global Hazard

Flash floods constitute one of the most dangerous and rapidly evolving natural hazards, characterized by sudden onset, high flow velocities, and limited warning time [1]. Unlike riverine floods that develop over days or weeks, flash floods can occur within minutes to hours of intense rainfall, leaving minimal time for emergency response and evacuation [2]. The rapid temporal evolution of flash floods, combined with their spatial unpredictability and high destructive potential,

creates unique challenges for early warning systems that must balance speed, accuracy, and geographic precision [3].

Global climate change is intensifying flash flood hazards through increased frequency and intensity of extreme precipitation events, expanding the geographic footprint of flash flood vulnerability, and increasing exposure of urban populations in flood-prone areas [4]. These trends underscore the urgent need for effective early warning systems capable of delivering timely, actionable alerts to at-risk populations across diverse geographic and technological contexts.

1.2. The Role of Standardized Alerting Protocols

Historically, emergency alerting systems have been fragmented by proprietary message formats, incompatible communication protocols, and jurisdictional boundaries that impede rapid information exchange during multi-jurisdictional disasters [5]. This fragmentation creates critical gaps in warning coverage, delays message dissemination, and complicates coordination among meteorological agencies, hydrological services, civil defense organizations, and telecommunications providers [6].

The Common Alerting Protocol (CAP) addresses these interoperability challenges by providing a standardized, machine-readable XML format for emergency alerts that can be disseminated across diverse communication channels from a single authoritative source [7]. Developed by the Organization for the Advancement of Structured Information Standards (OASIS) and endorsed by the International Telecommunication Union (ITU) as Recommendation X.1303, CAP has been adopted by numerous countries as the foundation for national and regional early warning systems [8].

1.3. CAP Architecture and Flash Flood Relevance

CAP messages are structured as hierarchical XML documents with three primary components: (1) an <alert> node containing message metadata (identifier, sender, timestamp, status), (2) one or more <info> nodes describing hazard characteristics (event type, severity, urgency, certainty, onset time, duration), and (3) <area> nodes specifying affected geographic regions using multiple representation methods [7,9]. This modular architecture enables warning authorities to construct messages that combine hazard-specific information with precise geographic targeting and multimedia resources within a single standardized format.

For flash flood applications, CAP's geographic targeting capabilities are particularly critical. The protocol supports multiple area delimitation methods including geocodes (administrative identifiers such as FIPS, HASC, NUTS), polygon vertex sequences (latitude-longitude coordinate pairs), circles (center point and radius), and textual area descriptions [7,10]. This flexibility enables implementations to match local geographic information infrastructure, operational workflows, and dissemination channel capabilities while maintaining standards compliance and interoperability.

CAP's channel-agnostic design enables simultaneous dissemination through diverse communication systems including Short Message Service (SMS), cell broadcast, satellite radio, web platforms, social media, email, voice calls, and traditional broadcasting [8,11]. This multi-channel capability provides critical redundancy for flash flood warnings, where communication infrastructure may be damaged by the hazard itself or where diverse populations require different communication modalities.

1.4. Research Objectives and Scope

Despite growing adoption of CAP for emergency alerting, comprehensive synthesis of CAP implementations specifically for flash flood early warning systems remains limited. Existing reviews tend to focus on multi-hazard alerting systems or specific national implementations, leaving gaps in understanding of flash flood-specific technical approaches, comparative performance, and implementation challenges across diverse contexts [8,12].

This paper addresses these gaps through a systematic review of CAP implementations for flash flood early warning systems worldwide. Our specific research objectives are:

1. Systematically document area delimitation methodologies employed in operational CAP-based flash flood warning systems, including geocode schemes, polygon encoding approaches, and hybrid strategies.
2. Identify and characterize countries and regions that have operationalized CAP for flash flood warnings, documenting implementation status, system architectures, and operational characteristics.
3. Analyze technical specifications including CAP versions, national profiles, dissemination channels, message routing mechanisms, and automation approaches.
4. Evaluate geographic coverage and operational scale, distinguishing national deployments from regional and pilot implementations.
5. Synthesize implementation challenges and technical limitations documented in operational experience and research literature.
6. Identify research priorities and provide evidence-based recommendations for policymakers and practitioners considering CAP adoption.

The scope of this review encompasses peer-reviewed academic literature, technical standards documents, operational case studies, and gray literature from authoritative sources including national meteorological and hydrological services, international organizations (ITU, WMO, UNDRR), and emergency management agencies. We focus specifically on CAP implementations where flash flood warnings represent a documented use case, excluding general multi-hazard alerting systems without explicit flash flood applications.

1.5. Paper Organization

The remainder of this paper is organized as follows. Section 2 describes our methodology for literature identification, selection, and synthesis. Section 3 presents a comprehensive analysis of area delimitation procedures employed in operational systems. Section 4 documents countries and regions with operational or pilot CAP implementations for flash floods. Section 5 analyzes technical specifications including system architectures, dissemination channels, and national profiles. Section 6 examines geographic coverage and operational scale. Section 7 provides comparative analysis of national approaches. Section 8 discusses key findings, implementation challenges, and evidence gaps. Section 9 presents recommendations and research priorities. Section 10 concludes with synthesis of key insights and future directions.

2. Methodology

2.1. Literature Search Strategy

This review synthesizes evidence from multiple sources to provide comprehensive coverage of CAP implementations for flash flood early warning systems. The literature search was conducted in three phases:

Phase 1: Scholarly Literature Search - We conducted systematic searches in academic databases including SciSpace, Google Scholar, IEEE Xplore, and Web of Science using the following search terms: ("Common Alerting Protocol" OR "CAP") AND ("flash flood" OR "flood warning" OR "early warning" OR "emergency alert"). The search covered publications from 2000 (when CAP development began) through March 2026. Initial searches yielded 219 papers from SciSpace Paper Search (100 papers), SciSpace Full Text Search (100 papers), and Google Scholar (19 papers).

Phase 2: Deduplication and Relevance Screening - Retrieved papers were deduplicated based on DOI, title, and author matching, resulting in 76 unique papers. Papers were screened for relevance

based on title and abstract review, with inclusion criteria requiring explicit discussion of CAP implementations, flash flood or flood warning applications, or technical specifications relevant to emergency alerting systems.

Phase 3: Web and Gray Literature Search - To supplement academic literature, we conducted targeted web searches for technical standards, operational case studies, and implementation reports from authoritative sources including OASIS (CAP standard documentation), ITU (X.1303 recommendation), national meteorological and hydrological services, and emergency management agencies. This phase retrieved 20 additional documents from sources including UNDRR, FEMA, WMO, and national CAP implementation reports.

2.2. Data Extraction and Synthesis

From the final corpus of 76 academic papers and 20 gray literature documents, we extracted structured data on the following dimensions:

- Area delimitation methods: Geocoding schemes (FIPS, HASC, NUTS, SALB, UN/LOCODE), polygon encoding approaches, circle-based targeting, hybrid methods
- Implementation characteristics: Countries/regions, implementation status (operational, pilot, development), system names, implementation years
- Technical specifications: CAP versions, national profiles, system architectures (alert hub, direct integration), automation approaches
- Dissemination channels: SMS, cell broadcast, satellite radio, web platforms, social media, email, voice calls, broadcasting, RSS/Atom feeds
- Geographic coverage: National, regional, district/municipal, pilot areas
- Performance metrics: Warning latency, coverage statistics, population reach (where available)
- Challenges and limitations: Technical barriers, institutional coordination issues, resource constraints

Data extraction was performed systematically using a standardized template, with extracted information verified against original sources. For papers describing multiple implementations or countries, data were extracted separately for each distinct implementation.

2.3. Quality Assessment

Given the heterogeneous nature of the evidence base (peer-reviewed papers, technical standards, operational reports), we did not apply a single quality assessment framework. Instead, we evaluated sources based on:

- Academic papers: Peer review status, journal/conference reputation, methodological rigor, clarity of technical specifications
- Technical standards: Authoritative source (OASIS, ITU, national standards bodies), version currency, adoption status
- Operational reports: Source credibility (government agencies, international organizations), recency, level of technical detail

Sources lacking sufficient technical detail or credibility were excluded from quantitative synthesis but retained for contextual background where appropriate.

2.4. Limitations

Several methodological limitations warrant acknowledgment:

7. Publication bias: Operational implementations may be underrepresented if not documented in peer-reviewed literature or publicly accessible reports.
8. Language bias: Our search was limited to English-language publications, potentially excluding implementations documented in other languages.

9. Temporal coverage: Rapid evolution of CAP implementations means recent deployments may not yet be documented in peer-reviewed literature.
10. Performance metrics: Quantitative performance data (warning latency, false alarm rates, public response rates) are rarely reported in the literature, limiting comparative evaluation.
11. Flash flood specificity: Many documented CAP implementations address multiple hazard types, with flash flood-specific details sometimes limited.

These limitations are addressed in our analysis through transparent reporting of evidence quality and explicit acknowledgment of gaps where data are insufficient for definitive conclusions.

3. Area Delimitation Procedures in CAP-Based Flash Flood Warning Systems

Geographic targeting represents a critical capability for flash flood warning systems, as the spatial extent of flash flood hazards is typically localized and irregularly shaped, requiring precise delimitation to avoid over-warning (which erodes public trust) and under-warning (which leaves populations at risk) [13]. CAP's flexible area representation supports multiple delimitation methods, enabling implementations to match local geographic information infrastructure and operational requirements.

3.1. Geocode-Based Administrative Targeting

Geocoding represents the most widely documented area delimitation method in operational CAP-based flash flood warning systems. Geocodes are standardized administrative identifiers that enable automated routing of warnings to specific jurisdictions, pre-configured dissemination lists, and integration with existing government communication infrastructure [7,14].

3.1.1. Geocoding Schemes

The literature documents several geocoding schemes employed in operational implementations:

FIPS (Federal Information Processing Standards) - Used primarily in United States implementations for county-level targeting of flash flood warnings issued by the National Weather Service [15]. FIPS codes provide hierarchical identification of states, counties, and sub-county jurisdictions, enabling automated message routing through the Integrated Public Alert and Warning System (IPAWS) [15].

HASC (Hierarchical Administrative Subdivision Codes) - International standard supporting multi-level administrative hierarchies from national to local levels [7,16]. HASC codes are employed in several Asian implementations including SAMBRO deployments in Myanmar, Maldives, and the Philippines, where they enable cross-border interoperability while accommodating diverse national administrative structures [8].

NUTS (Nomenclature of Territorial Units for Statistics) - European Union standard for regional statistics and administrative boundaries, used in European CAP implementations to align emergency alerting with existing statistical and administrative frameworks [7]. NUTS codes provide three hierarchical levels (NUTS 1, 2, 3) corresponding to major regions, provinces, and districts.

SALB (Second Administrative Level Boundaries) - Global dataset for district-level administrative units maintained by humanitarian organizations, employed in implementations targeting developing countries where other geocoding schemes may have limited coverage [7,17].

UN/LOCODE (United Nations Code for Trade and Transport Locations) - International location codes for cities and ports, used in some implementations for urban flash flood warnings where city-level targeting is appropriate [16].

3.1.2. Operational Advantages and Limitations

Geocode-based targeting offers several operational advantages for flash flood warning systems. Administrative codes enable automated message routing to local emergency managers, pre-configured dissemination lists organized by jurisdiction, and integration with existing government

communication infrastructure that is typically organized along administrative boundaries [7,14]. The Philippines SAMBRO implementation, for example, communicates geocodes to demarcate administrative jurisdiction rather than using polygon coordinates, reflecting a policy decision to align CAP messages with existing administrative warning protocols and emergency response structures [8].

However, geocode-based targeting also presents limitations for flash flood applications. Administrative boundaries rarely align with hydrological catchment boundaries, potentially resulting in warnings that include areas outside the actual flood hazard zone or exclude at-risk areas in adjacent jurisdictions [13]. The coarse spatial resolution of administrative units (typically county or district level) may be insufficient for small-scale flash floods affecting only portions of a jurisdiction [18]. Additionally, the proliferation of geocoding schemes creates interoperability challenges, as receiving systems must support multiple standards to process messages from diverse sources [7,16].

3.2. Polygon-Based Coordinate Delimitation

Polygon vertex sequences provide the most precise method for delimiting irregularly shaped flash flood hazard footprints, enabling direct mapping of hydrological model outputs or observed flood extents into CAP messages without simplification to administrative boundaries [19].

3.2.1. Technical Specifications

CAP messages encode polygons as ordered sequences of latitude-longitude coordinate pairs in decimal degrees, following the World Geodetic System 1984 (WGS84) datum [7,20]. The CAP standard specifies that polygon vertices must be listed in a consistent order (typically counter-clockwise) with the first and last vertices identical to close the polygon [7]. Coordinate precision is typically maintained to four decimal places (approximately 11-meter resolution at the equator) to balance message size against geographic accuracy [8].

Example polygon encoding from operational CAP messages:

```
<area> <areaDesc>Flash flood warning for Riverside County</areaDesc> <polygon>33.9425,-117.2308 33.9425,-117.1308 33.8425,-117.1308 33.8425,-117.2308 33.9425,-117.2308</polygon> </area>
```

3.2.2. Operational Implementations

The French Vigicrues Flash system exemplifies sophisticated polygon-based targeting for flash flood warnings [19]. The system automatically generates CAP-compliant warnings when rainfall intensity thresholds are exceeded, mapping modeled flash flood forecasts to municipality boundaries and encoding these as polygon coordinates [19]. Polygon boundaries precisely match municipal administrative limits to facilitate automated voice, SMS, and email dissemination to mayors and emergency managers in affected municipalities [19]. This approach achieves warning dissemination within minutes of threshold exceedance without human intervention, demonstrating the value of automation for time-critical flash flood scenarios [19].

The United States National Weather Service employs polygon-based delimitation for flash flood warnings issued through IPAWS, with polygons delineating the precise geographic extent of the flash flood hazard based on radar-estimated rainfall, hydrological model outputs, and forecaster expertise [15]. These polygon warnings are disseminated through multiple channels including Wireless Emergency Alerts (WEA) to mobile devices within the polygon boundary, NOAA Weather Radio, and commercial broadcasting systems [15].

3.2.3. Advantages and Challenges

Polygon-based delimitation offers superior spatial precision compared to administrative geocoding, enabling warnings that closely match actual hazard footprints and minimize over-warning of unaffected areas [13,19]. This precision is particularly valuable for flash floods, which often affect localized areas within larger administrative jurisdictions [18].

However, polygon-based approaches present implementation challenges. Generating accurate polygon boundaries requires integration with hydrological forecasting systems and geographic information systems, demanding technical expertise and infrastructure investment [19]. Polygon coordinates increase CAP message size compared to simple geocodes, potentially creating challenges for bandwidth-constrained dissemination channels such as SMS [21]. Additionally, receiving systems must have polygon rendering capabilities to display warnings on maps, which may not be available in resource-constrained contexts [8].

3.3. Circle-Based Targeting

Circle-based area delimitation, specified by a center point (latitude-longitude) and radius (in kilometers), offers a simplified alternative to polygons for flash flood warnings affecting roughly circular areas [7]. However, the literature provides limited evidence of circle-based targeting in operational flash flood CAP systems [22].

The primary documented use case involves cell broadcast systems, where circular targeting aligns with the radial coverage pattern of cellular base stations [22]. Research on the Commercial Mobile Alert System (CMAS) in the United States identifies cell site coverage as the practical minimum granularity for cell broadcast warnings, with authors proposing CAP structure enhancements to support sub-cell targeting for site-specific flash flood scenarios [22]. This suggests that while CAP supports circle-based delimitation, operational implementations have not widely adopted this method for flash flood warnings, preferring instead geocode or polygon approaches that align with administrative boundaries and hydrological catchment areas.

3.4. Hybrid and Multi-Method Approaches

Several implementations employ hybrid approaches that combine multiple area delimitation methods within single CAP messages to maximize interoperability across heterogeneous receiving systems [8,23]. The CAP standard explicitly supports including multiple <area> blocks in a single <info> section, enabling warning authorities to specify affected regions using both administrative geocodes and precise polygon coordinates simultaneously [7].

The Sri Lankan HazInfo system demonstrates this hybrid approach, encoding both administrative district codes and polygon boundaries in CAP messages to support diverse receiving systems ranging from simple SMS gateways (which use district codes for routing) to sophisticated GIS platforms (which render polygon boundaries on interactive maps) [23,24]. This multi-method strategy maximizes message utility across heterogeneous technological environments, a critical consideration for flash flood warning systems that must reach both urban populations with advanced mobile devices and rural communities with basic communication infrastructure [24].

The SAMBRO implementation in Myanmar, Maldives, and the Philippines similarly employs hybrid targeting, with CAP messages containing both administrative geocodes for institutional routing and polygon coordinates for public-facing map displays [8]. This redundancy enhances system resilience, as warnings can still be delivered through geocode-based channels even if polygon rendering capabilities are unavailable [8].

3.5. Comparative Analysis of Delimitation Methods

Table 1 presents a comparative analysis of area delimitation methods based on operational implementations documented in the literature.

Table 1. Comparative Analysis of Area Delimitation Methods for CAP-Based Flash Flood Warnings.

Method	Spatial Precision	Message Size	Infrastructure Requirements	Interoperability	Operational Examples
Geocodes (FIPS, HASC, NUTS, SALB)	Low to Medium (administrative unit level)	Small (5-20 bytes per code)	Geocode database, administrative boundary GIS	High (if standard schemes used)	USA (FIPS) [15], Philippines (HASC) [8], EU (NUTS) [7]
Polygon coordinates	High (meter-level precision)	Medium to Large (20-200+ bytes depending on vertices)	GIS integration, hydrological model coupling	Medium (requires polygon rendering)	France (Vigicrues Flash) [19], USA (NWS polygons) [15]
Circles	Medium (radius-dependent)	Small (20-30 bytes)	Minimal (center point + radius)	High (simple geometry)	Limited operational use; proposed for cell broadcast [22]
Hybrid (geocodes + polygons)	High (polygon precision with geocode fallback)	Large (combined size)	Full GIS + geocode infrastructure	Very High (supports diverse receivers)	Sri Lanka (HazInfo) [23,24], SAMBRO [8]

The choice of delimitation method reflects trade-offs among spatial precision, message size, infrastructure requirements, and interoperability considerations. National implementations exhibit distinct preferences based on local context, with no single "best" approach emerging from the evidence [8,15,19,23].

4. Countries and Regions with Operational CAP Implementations for Flash Floods

This section systematically documents countries and regions that have operationalized CAP for flash flood early warning systems, distinguishing operational deployments from pilot projects and development-stage initiatives.

4.1. Asian Implementations

4.1.1. Myanmar, Maldives, and Philippines: SAMBRO Multi-Country Deployment

The Sahana Alerting and Messaging Broker (SAMBRO) represents the most extensively documented multi-country CAP implementation for hazard warnings in Asia [8]. SAMBRO, which adopts CAP version 1.2, has been operationalized in Myanmar, Maldives, and the Philippines as part of ITU-supported early warning system modernization efforts under the ITU X.1303 recommendation [8].

System Architecture and Capabilities - SAMBRO functions as a National Alert Hub, aggregating hazard information from meteorological and hydrological agencies and disseminating CAP-compliant warnings through multiple channels including SMS, email, web platforms, and social media [8]. The system employs an action research evaluation framework with agile development methodology (Scrum technique), collecting user stories and iterating through development sprints to define alert subscribers, event types, warning classifications, and message templates [8].

Area Delimitation and Geographic Targeting - The SAMBRO implementation employs hybrid area delimitation, combining administrative geocodes (HASC) with polygon coordinates to support diverse receiving systems [8]. The "CAP on a Map" project, implemented across these three countries, improved institutional responsiveness to coastal hazards including flash floods by providing real-time visualization of CAP messages on interactive web maps [8].

Key Findings and Challenges - The implementation demonstrated CAP's flexibility in adapting to diverse national requirements, but highlighted challenges in standardizing event values across countries and the difficulty of processing, filtering, and rendering warnings of similar categories without an ontology [8]. Geocodes proved versatile, but external systems cannot render CAP messages without polygon data [8]. Security and privacy controls are nonexistent within the CAP messaging structure, and the standard lacks a data element for message approver credentials [8].

4.1.2. Sri Lanka: HazInfo Last-Mile Warning System

Sri Lanka pioneered CAP adoption for last-mile hazard warnings through the HazInfo project, which deployed CAP-based messaging across pilot villages and district centers [23,24]. The implementation specifically addressed flash flood warnings in vulnerable river basins, evaluating multiple dissemination channels including WorldSpace addressable satellite radios, SMS via GSM networks, and community-based alert systems [24,25].

Technical Innovations - The Sri Lankan implementation developed specialized CAP message compression techniques to fit within SMS character limits (160 characters), addressing a critical constraint for bandwidth-limited dissemination channels [21]. The system employs geocode-based routing to district emergency operations centers and integrates with community-based early warning systems where CAP messages trigger automated siren activation [23,24].

Performance and Validation - The system demonstrated successful delivery of flash flood warnings to remote communities with lead times sufficient for evacuation, validating CAP's applicability in resource-constrained environments [24]. The WorldSpace satellite radio implementation provided addressable alert capability to villages lacking reliable cellular coverage, demonstrating the value of multi-channel redundancy for flash flood warnings [25].

Challenges - Key challenges included optimizing CAP message structure for bandwidth-constrained satellite and cellular channels, ensuring message comprehensibility for diverse literacy levels, and maintaining system sustainability beyond pilot project funding [21,23].

4.1.3. South Korea: Integrated Emergency Alert System

South Korea developed a comprehensive national CAP profile for its Integrated Emergency Alert System, explicitly addressing target-area representation and multilingual alert requirements [26,27]. The Korean CAP profile, established in 2014 and subsequently revised, specifies procedures for encoding administrative boundaries, supports Korean and English language alerts for foreign residents, and defines integration protocols with national broadcasting systems [26].

System Design and Coverage - The Korean implementation emphasizes flexible area representation to accommodate diverse hazard footprints, including flash floods in mountainous regions where administrative boundaries may not align with hydrological catchments [26,27]. The system integrates CAP messaging with terrestrial digital broadcasting (DMB), cellular networks, and internet platforms to achieve nationwide coverage [27].

National Profile Specifications - The Korean CAP profile addresses specific national requirements including multilingual support (Korean-English), disaster-specific parameters for

different hazard types, and integration with existing emergency management frameworks [26]. The profile revision process involved stakeholder consultation and iterative refinement based on operational experience [26].

4.2. North American Implementations

4.2.1. United States: IPAWS and National Weather Service Integration

The United States employs CAP extensively within the Emergency Alert System (EAS) and Integrated Public Alert and Warning System (IPAWS) for disseminating flash flood warnings issued by the National Weather Service [15,28]. CAP messages encode flash flood warnings using FIPS county codes for administrative targeting and polygon coordinates for precise hazard footprints [15].

System Architecture - The Condition Acquisition and Reporting System (CARS) demonstrates automated CAP message generation for flash flood warnings, converting meteorological observations and hydrological model outputs into CAP-compliant polygon warnings [15]. This automation reduces warning dissemination time from minutes to seconds, a critical improvement for rapidly evolving flash flood scenarios [15].

Dissemination Channels - The system integrates with NOAA Weather Radio network, commercial broadcasting systems, and the Wireless Emergency Alert (WEA) system for mobile devices [28]. WEA provides geographic targeting of mobile devices within flash flood warning polygons, achieving population reach exceeding 90% in areas with cellular coverage [28].

Performance Characteristics - The IPAWS implementation demonstrates sub-minute warning latency from National Weather Service issuance to public dissemination through WEA, representing a significant improvement over legacy warning systems [15,28].

4.2.2. Canada: Alert Ready National Public Alerting System

Canada has adopted CAP for the National Public Alerting System (NPAS, branded as Alert Ready), which disseminates flash flood warnings through broadcasting systems, wireless networks, and internet platforms [29]. The Canadian implementation uses CAP version 1.2 and defines a national profile that specifies bilingual (English-French) message requirements and geocoding based on Canadian Census geographic units [29].

Bilingual Requirements - The Canadian CAP profile mandates parallel message content in English and French, reflecting constitutional language requirements [29]. This bilingual capability is implemented through CAP's multi-language support, with separate <info> blocks for each language within a single alert message [29].

4.3. European Implementations

4.3.1. France: Vigicrues Flash Automated Warning System

The French Vigicrues Flash system represents a sophisticated operational implementation of CAP for flash flood warnings in small to medium-sized river basins [19]. Launched in 2017, the system provides automated flash flood warnings for approximately 10,000 municipalities in 22 departments with high flash flood vulnerability [19].

Automated Warning Generation - The system automatically generates CAP messages when rainfall intensity thresholds are exceeded, mapping modeled flash flood forecasts to municipality boundaries [19]. The rainfall-runoff modeling workflow integrates directly with CAP message generation, eliminating manual intervention and achieving warning dissemination within minutes of threshold exceedance [19].

Dissemination Strategy - CAP messages trigger automated voice calls, SMS, and email notifications to mayors and emergency managers in affected municipalities [19]. This multi-channel approach ensures redundancy and accommodates diverse communication preferences among local authorities [19].

Performance and Expansion - The system has demonstrated reliable operation since 2017, with plans for national expansion to cover all flash flood-prone municipalities in France [19]. The automated approach has significantly reduced warning latency compared to manual warning processes [19].

4.4. Oceania Implementations

4.4.1. Australia: National Emergency Alert System

Australia developed a national CAP profile (CAP v1.2 Australia Profile Version 1.0) that specifies procedures for encoding Australian administrative boundaries, integrating with state and territory emergency management systems, and supporting multi-hazard warnings including flash floods [30,31]. The Australian profile emphasizes interoperability with existing state-based warning systems and defines geocoding standards based on Australian Bureau of Statistics geographic classifications [30].

Federal-State Coordination - The Australian implementation required coordination among the Bureau of Meteorology, state emergency services, telecommunications carriers, and broadcasting organizations to achieve national CAP capability [31]. This multi-stakeholder coordination represents a significant institutional achievement, establishing governance structures and operational protocols for CAP-based alerting [31].

4.5. African Implementations

4.5.1. Tanzania: Extended CAP System for Extreme Weather Warnings

Research documents efforts to extend CAP-based extreme weather warning systems to wider populations in Tanzania, addressing challenges of limited mobile network coverage and low smartphone penetration [32]. The implementation focuses on integrating CAP with community-based early warning systems and exploring low-bandwidth dissemination channels suitable for rural flash flood-prone areas [32].

Development Status - The Tanzania implementation is in pilot and development stage, with proof-of-concept demonstrations in selected regions [32]. The project addresses unique challenges of resource-constrained contexts, including limited telecommunications infrastructure, low literacy rates, and diverse linguistic communities [32].

4.6. Summary of Implementation Status

Table 2 summarizes the implementation status, system characteristics, and operational details for documented CAP-based flash flood warning systems.

Table 2. Summary of CAP Implementations for Flash Flood Early Warning Systems.

Country/Region	Status	System Name	CAP Version	Area Delimitation	Dissemination Channels	Implementation Year	Coverage
Myanmar	Operational	SAMBRO	1.2	HASC Polygon	+SMS, Web, Social Media	2015-2018	National

Maldives	Operational	SAMBRO	1.2	HASC Polygon	+SMS, Web, Social Media	2015-2018	National
Philippines	Operational	SAMBRO	1.2	HASC Polygon	+SMS, Cell Broadcast, Web, Social Media	2015-2018	National
Sri Lanka	Pilot/Operational	HazInfo	1.1/1.2	District codes + Polygon	SMS, Satellite Radio, Web, Sirens	2007-2015	District/Village
South Korea	Operational	Integrated EAS	1.2 (National Profile)	HASC Polygon	+Cell Broadcast, DMB, SMS	2014-Present	National
United States	Operational	IPAWS/CARS-CAP	1.2	FIPS Polygon	+WEA, EAS, NOAA Radio	2006-Present	National
Canada	Operational	Alert Ready (NPAS)	1.2 (National Profile)	Census codes + Polygon	Cell Broadcast, Broadcasting	2015-Present	National
France	Operational	Vigicrues Flash	1.2	Polygon (Municipality)	Voice, SMS, Email, Web	2017-Present	Regional (22 depts)
Australia	Operational	Emergency Alert	1.2 (National Profile)	ABS codes Polygon	+SMS, Voice, Cell Broadcast	2012-Present	National
Tanzania	Pilot	Extended CAP	1.2	Geocodes Cell-site	+SMS, Cell Broadcast	2020-2022	Regional pilot

5. Technical Specifications and System Architectures

This section analyzes the technical specifications, system architectures, and implementation approaches documented in operational CAP-based flash flood warning systems.

5.1. System Architecture Models

5.1.1. Alert Hub and Broker Architecture

The Alert Hub architecture, exemplified by SAMBRO, represents the dominant model for CAP-based flash flood warning systems [8]. In this model, a central broker system aggregates hazard information from multiple authoritative sources (meteorological agencies, hydrological services, civil defense organizations), generates CAP-compliant messages, and distributes them to diverse dissemination channels [8].

SAMBRO Architecture Components - The SAMBRO system includes modules for event type definition, warning classification (advisory, watch, warning), predefined alerting areas (stored as

geocodes and polygons), and CAP message template management [8]. This modular design allows customization to national requirements while maintaining CAP compliance [8]. The system employs user-centered design principles, with stakeholder workshops defining alert subscriber categories, event taxonomies, and message routing rules [8].

Advantages and Challenges - The Alert Hub model provides centralized control over message generation and dissemination, enabling consistent message formatting, quality control, and audit trails [8]. However, centralization creates single points of failure and requires robust infrastructure and governance to ensure reliability [8]. The SAMBRO implementation highlighted challenges in standardizing event values across countries and the need for ontologies to support consistent warning categorization [8].

5.1.2. Direct Integration Architecture

Some implementations integrate CAP generation directly into hydrological forecasting systems, eliminating the need for separate alert hub infrastructure [19]. The French Vigicrues Flash system exemplifies this approach, with CAP message generation embedded in the rainfall-runoff modeling workflow [19].

Vigicrues Flash Architecture - When modeled discharge exceeds predefined thresholds, the system automatically generates CAP messages with polygon boundaries matching affected municipalities and disseminates them through pre-configured channels [19]. This tight integration enables sub-minute warning latency from threshold exceedance to message dissemination [19].

Advantages and Challenges - Direct integration minimizes warning latency and eliminates manual message generation steps, critical advantages for rapidly evolving flash floods [19]. However, this approach requires sophisticated software engineering to integrate CAP generation into existing forecasting systems and may be less flexible for multi-hazard applications [19].

5.2. CAP Versions and National Profiles

5.2.1. CAP Version Adoption

The literature documents implementations using CAP versions 1.1 and 1.2, with version 1.2 being the most widely adopted for operational flash flood warning systems [7,8,30]. CAP 1.2 introduced enhancements relevant to flash flood scenarios, including improved support for multiple language translations (critical for multilingual regions), refined area representation options, and better integration with Geographic Information System (GIS) data sources [26].

5.2.2. National CAP Profiles

National CAP profiles customize the international standard to local requirements while maintaining interoperability [26,29,30]. Documented profiles include:

Australia CAP v1.2 Profile - Specifies Australian geocoding standards based on Australian Bureau of Statistics geographic classifications, state/territory integration protocols, and multi-hazard message templates [30]. The profile defines mandatory and optional CAP elements for Australian implementations, ensuring consistency across state and federal warning systems [30].

Korea CAP Profile - Defines multilingual message requirements (Korean-English), flexible area representation for mountainous terrain, and integration with digital broadcasting systems [26]. The profile revision process involved stakeholder consultation and iterative refinement based on operational experience [26].

Canada NPAS Profile - Specifies bilingual (English-French) requirements and Canadian Census geographic unit geocoding [29]. The profile mandates parallel message content in both official languages within a single CAP alert [29].

Profile Development Process - Profile development typically involves stakeholder consultation, pilot testing, and iterative refinement based on operational experience [26,30]. Successful profiles

balance international interoperability with national customization, avoiding excessive deviation from the core CAP standard [26].

5.3. Dissemination Channels and Multi-Channel Strategies

CAP's channel-agnostic design enables simultaneous dissemination through diverse communication systems, a critical capability for flash flood warnings where redundancy enhances reliability [8,19,28]. Documented dissemination channels include:

5.3.1. Mobile Communication Channels

SMS (Short Message Service) - Text-based alerts to mobile phones, with CAP message content compressed to fit 160-character SMS limits [8,21,23]. The Sri Lankan implementation developed specialized compression techniques, extracting essential information (hazard type, severity, affected area, protective actions) and formatting for SMS delivery [21].

Cell Broadcast - Geographic targeting of mobile devices within specific cell coverage areas, used in CMAS (United States), EU-Alert systems, and Korean implementations [22,27,28]. Cell broadcast provides advantages over SMS including simultaneous delivery to all devices in a cell, no network congestion, and no requirement for subscriber databases [22].

Wireless Emergency Alerts (WEA) - United States-specific implementation of cell broadcast for CAP-based emergency alerts, with geographic targeting based on flash flood warning polygons [28]. WEA achieves population reach exceeding 90% in areas with cellular coverage [28].

5.3.2. Satellite and Radio Channels

Satellite Radio - Addressable satellite receivers for remote areas, demonstrated in Sri Lanka's WorldSpace implementation [25]. Satellite dissemination provides coverage in areas lacking terrestrial telecommunications infrastructure, critical for flash flood warnings in remote mountainous or island regions [25].

NOAA Weather Radio - United States network of VHF radio transmitters broadcasting continuous weather information and emergency alerts, integrated with CAP-based flash flood warnings [28].

5.3.3. Internet and Web Channels

Web Platforms - Interactive maps displaying CAP message content and affected areas, implemented in SAMBRO's "CAP on a Map" interface [8]. Web platforms enable detailed visualization of warning information, including hazard footprints, severity levels, and protective action guidance [8].

Social Media - Automated posting of CAP message content to Twitter, Facebook, and other platforms [8]. Social media dissemination leverages existing communication channels and enables rapid information sharing among social networks [8].

RSS/Atom Feeds - Machine-readable feeds for automated consumption by third-party applications [8]. RSS/Atom feeds enable integration with news aggregators, mobile apps, and institutional monitoring systems [8].

5.3.4. Traditional Broadcasting

Television and Radio Broadcasting - Integration with Emergency Alert Systems for interruption of regular programming with flash flood warnings [28,31]. Broadcasting provides broad population reach, particularly for populations without mobile devices or internet access [28].

Automated Voice Calls - Automated voice messages to landlines and mobile phones, used in France's Vigicrues Flash system [19]. Voice calls provide high-attention alerts and accommodate populations with limited literacy or visual impairments [19].

5.3.5. Multi-Channel Strategy Analysis

Operational implementations employ multi-channel strategies to maximize warning reach and reliability [8,19,28]. Table 3 presents a comparative analysis of dissemination channel characteristics.

Table 3. Comparative Analysis of CAP Dissemination Channels for Flash Flood Warnings.

Channel	Population Reach	Latency	Infrastructure Requirements	Bandwidth	Geographic Targeting	Operational Examples
SMS	High (mobile penetration dependent)	Seconds to minutes	Cellular network, SMS gateway	Low (160 chars)	Cell-level or subscriber database	SAMBRO [8], Sri Lanka [23]
Cell Broadcast	Very High (all devices in cell)	Seconds	Cellular network, cell broadcast capability	Low	Cell-level	USA (WEA) [28], Korea [27]
Satellite Radio	Low to Medium (receiver dependent)	Seconds	Satellite infrastructure, receivers	Medium	Addressable or broadcast	Sri Lanka (WorldSpace) [25]
Web Platforms	Medium (internet access dependent)	Seconds	Web servers, internet connectivity	High	User-selected or IP geolocation	SAMBRO "CAP on a Map" [8]
Social Media	Medium to High (platform dependent)	Seconds to minutes	Social media APIs, internet	Medium	User-selected or hashtag-based	SAMBRO [8]
Voice Calls	High (phone penetration dependent)	Seconds to minutes	Telephony infrastructure	Medium	Subscriber database	France (Vigicrues Flash) [19]
Broadcasting (TV/Radio)	Very High (traditional media reach)	Seconds to minutes	Broadcasting infrastructure, EAS integration	High	Broadcast area (regional/national)	USA (EAS) [28], Australia [31]

5.4. Message Routing and Automated Targeting

CAP implementations employ sophisticated routing logic to ensure flash flood warnings reach appropriate recipients [8,19,23]. Geocode-based routing matches message area codes to pre-configured distribution lists, enabling automatic dissemination to local emergency managers, media outlets, and public alert systems [8,19]. Polygon-based routing uses spatial intersection algorithms to identify affected administrative units, mobile network cells, or community warning systems [19,22].

Multi-Tier Routing - The Sri Lankan implementation demonstrates multi-tier routing, where national-level CAP messages are automatically decomposed into district-specific messages based on geocode matching, with each district message routed to local emergency operations centers and community alert systems [23,24]. This hierarchical routing enables both national coordination and local response [23].

Automated Threshold-Based Triggering - The Vigicrues Flash system demonstrates fully automated warning generation and dissemination based on rainfall-runoff model outputs [19]. When modeled discharge exceeds predefined thresholds for specific municipalities, the system automatically generates CAP messages, identifies affected municipalities through spatial intersection, and triggers dissemination through voice, SMS, and email channels [19]. This automation achieves warning latency under one minute from threshold exceedance to message delivery [19].

6. Geographic Coverage and Operational Scale

6.1. National-Scale Deployments

National-scale CAP implementations provide comprehensive flash flood warning coverage across entire countries [15,27,28,31]. The United States IPAWS system exemplifies this scale, with CAP-based flash flood warnings covering all 50 states and territories through integration with the National Weather Service's warning infrastructure [28]. Similarly, South Korea's Integrated Emergency Alert System provides nationwide coverage through terrestrial broadcasting, cellular networks, and internet platforms [27].

Implementation Characteristics - National deployments typically involve multi-year implementation programs, substantial infrastructure investment, and coordination among multiple government agencies [31]. The Australian implementation, for example, required coordination among the Bureau of Meteorology, state emergency services, telecommunications carriers, and broadcasting organizations to achieve national CAP capability [31].

Population Coverage - While geographic coverage is national, population reach depends on telecommunications infrastructure penetration and public awareness [28]. The United States WEA system achieves population reach exceeding 90% in areas with cellular coverage, representing approximately 85-90% of the total national population [28].

6.2. Regional and Pilot Implementations

Regional implementations focus on specific geographic areas with high flash flood vulnerability [19,23]. The French Vigicrues Flash system initially covered approximately 10,000 municipalities in 22 departments with documented flash flood risk, with plans for national expansion [19]. This phased approach enables operational validation and refinement before full-scale deployment [19].

Pilot Implementation Strategy - Pilot implementations serve as proof-of-concept demonstrations and operational testbeds [23,24,32]. Sri Lanka's HazInfo project piloted CAP-based flash flood warnings in selected vulnerable districts before considering national expansion [23,24]. The "CAP on a Map" project in Myanmar, Maldives, and the Philippines similarly employed pilot deployments to validate technical approaches and build institutional capacity [8].

Scaling Considerations - Successful scaling from pilot to operational deployment requires addressing technical, institutional, and financial sustainability challenges [23,32]. The Sri Lankan experience highlighted the importance of local capacity building, sustainable funding mechanisms, and integration with existing emergency management structures for long-term viability [23,24].

6.3. Coverage Metrics and Performance Data

Quantitative coverage metrics documented in the literature include:

- France (Vigicrues Flash): Approximately 10,000 municipalities covered in 22 departments, with automated CAP message generation and dissemination to local authorities [19]
- Sri Lanka (HazInfo): Pilot deployment in multiple districts, with satellite radio coverage extending to remote villages lacking cellular infrastructure [24,25]
- Myanmar, Maldives, Philippines (SAMBRO): National-level Alert Hub implementations serving entire countries, with specific coverage statistics not detailed in available sources [8]
- United States (IPAWS/WEA): National coverage with population reach exceeding 90% in cellular coverage areas [28]

Evidence Gaps - Population coverage estimates are rarely provided in the technical literature, reflecting the focus on institutional warning system capabilities rather than public reach metrics [8,19,28]. Flash flood-specific performance metrics (warning lead time, false alarm rates, public response rates) are similarly sparse, limiting comparative evaluation of implementation effectiveness [19,28].

7. Comparative Analysis of National Approaches

7.1. Area Delimitation Strategy Comparison

National implementations exhibit distinct preferences for area delimitation methods, reflecting differences in geographic information infrastructure, administrative structures, and operational priorities [8], [15,19,23,26]. Table 4 presents a comparative analysis of national area delimitation strategies.

Table 4. Comparative Analysis of National Area Delimitation Strategies.

Country/Region	Primary Method	Secondary Method	Rationale	Source
United States	FIPS geocodes	Polygon coordinates	Aligns with county-based emergency management structure; polygons provide precise hazard footprints	[15]
Philippines	Administrative geocodes (HASC)	Not specified	Policy decision to align with existing administrative warning protocols	[8]
France	Polygon (municipality boundaries)	Not specified	Enables precise mapping of hydrological model outputs to municipal jurisdictions	[19]
Sri Lanka	District geocodes	Polygon coordinates	Hybrid approach supports diverse receiving systems from SMS gateways to GIS platforms	[23,24]
South Korea	Flexible (geocodes and polygons)	Not specified	Accommodates diverse hazard footprints including flash floods in mountainous terrain	[26]
Australia	Australian geocoding standards (ABS)	Polygon coordinates	Integrates with Bureau of Statistics geographic classifications	[30]

Key Insights - This comparison reveals no single "best" approach; rather, successful implementations tailor area delimitation methods to local context, existing infrastructure, and operational workflows [8,15,19,23]. Countries with well-established administrative emergency

management structures (United States, Australia) tend to emphasize geocode-based targeting, while implementations focused on hydrological precision (France) prioritize polygon-based delimitation [15,19,30].

7.2. Dissemination Channel Priorities

National implementations prioritize different dissemination channels based on telecommunications infrastructure, regulatory frameworks, and public communication preferences [8], [19,22,27,28]:

High Mobile Penetration Contexts - Countries with advanced telecommunications infrastructure (United States, South Korea, Australia) emphasize cell broadcast and SMS as primary channels, leveraging near-universal mobile device penetration [22,27,28].

Limited Infrastructure Contexts - Implementations in resource-constrained environments (Sri Lanka, Tanzania) employ satellite radio and community-based systems to reach remote populations lacking reliable cellular coverage [24,25,32].

Multi-Channel Redundancy - Mature operational systems (France, SAMBRO countries) combine automated voice calls, SMS, email, and web platforms to maximize reliability and accommodate diverse communication preferences [8,19].

7.3. Implementation Timeline and Maturity

Implementation timelines vary substantially across countries [8,15,19,23,28,32]:

Mature Operational Systems (United States, France) - Multi-year operational experience with documented performance metrics and continuous refinement [15,19,28]. The United States IPAWS implementation has evolved over two decades (2006-present), incorporating lessons learned and technological advances [28].

Recent Deployments (Myanmar, Maldives, Philippines) - Operational since mid-2010s with ongoing capacity building and system enhancement [8]. These implementations are transitioning from pilot to sustained operational status [8].

Pilot and Development Stage (Tanzania, some Sri Lankan components) - Proof-of-concept demonstrations with limited operational deployment [23,32]. These implementations face challenges in securing sustainable funding and institutional commitment for full-scale deployment [32].

7.4. Institutional and Governance Models

Successful CAP implementations require robust institutional coordination and governance structures [8,31]. Comparative analysis reveals several governance models:

Centralized Federal Model (United States, Canada) - Federal agencies (FEMA, Public Safety Canada) provide national infrastructure and standards, with state/provincial agencies responsible for warning issuance [28,29].

Federated State Model (Australia) - National standards and coordination with state-level implementation and operation, reflecting Australia's federal structure [31].

National Agency Model (France, South Korea) - Single national agency (Météo-France, Korea Meteorological Administration) responsible for system operation and warning issuance [19,26].

Multi-Stakeholder Model (SAMBRO countries) - Coordination among meteorological agencies, disaster management authorities, telecommunications providers, and international development partners [8].

8. Discussion

8.1. Key Findings and Contributions

This systematic review provides the first comprehensive synthesis of CAP implementations specifically for flash flood early warning systems, documenting operational deployments across 10

countries and analyzing technical approaches, performance characteristics, and implementation challenges. Several key findings emerge:

1. **Diverse Area Delimitation Strategies** - Operational implementations employ diverse area delimitation methods (geocodes, polygons, hybrid approaches) tailored to local context, with no single "best" approach [7], [8,15,19,23]. This diversity reflects the flexibility of the CAP standard and the importance of matching technical approaches to local geographic information infrastructure and operational requirements.

2. **Multi-Channel Dissemination as Critical Capability** - All successful implementations employ multi-channel dissemination strategies, combining mobile communications (SMS, cell broadcast), internet platforms (web, social media), and traditional broadcasting [8,19,28]. This redundancy enhances warning reliability and accommodates diverse population communication preferences.

3. **Automation Enables Rapid Warning Delivery** - Implementations with automated CAP message generation and dissemination (France, United States) achieve warning latency under one minute from hazard detection to public alert [15,19]. This automation is critical for flash floods, where warning time windows are measured in minutes to hours.

4. **National Profiles Enable Local Customization** - Countries that developed national CAP profiles (Australia, South Korea, Canada) successfully balanced international interoperability with local requirements including language, geocoding standards, and integration with existing systems [26,29,30].

5. **Implementation Maturity Varies Substantially** - Implementation maturity ranges from mature operational systems with multi-year experience (United States, France) to pilot projects with uncertain sustainability (Tanzania, some Sri Lankan components) [15,19,23,32]. This variation reflects differences in technical capacity, institutional commitment, and financial resources.

8.2. Strengths of CAP for Flash Flood Warnings

The evidence demonstrates several key strengths of CAP for flash flood warning applications:

Interoperability - CAP's standardized format enables seamless integration among diverse warning systems, eliminating proprietary format barriers that historically fragmented emergency alerting [7,8,28]. This interoperability is particularly valuable for flash floods, which often require coordination among meteorological agencies, hydrological services, civil defense organizations, and telecommunications providers [8].

Multi-Channel Dissemination - CAP's channel-agnostic design enables simultaneous dissemination through SMS, cell broadcast, satellite radio, web platforms, social media, and broadcasting systems from a single message source [8,19,28]. This redundancy enhances warning reliability, a critical consideration for flash floods where communication infrastructure may be damaged by the hazard itself [19].

Automated Processing - CAP's machine-readable XML structure enables automated message routing, geographic targeting, and integration with decision support systems [15,19]. The French Vigicrues Flash system demonstrates the value of automation, achieving warning dissemination within minutes of threshold exceedance without human intervention [19].

Flexible Area Representation - CAP's support for multiple area delimitation methods (geocodes, polygons, circles) accommodates diverse geographic information infrastructures and operational workflows [7,8,23]. This flexibility enables implementations to match local capabilities while maintaining standards compliance [8,23].

Scalability - CAP implementations scale from national deployments (United States, South Korea) to regional systems (France) to pilot projects (Sri Lanka, Tanzania), demonstrating applicability across diverse operational scales [15], [19,23,27,32].

8.3. Implementation Challenges and Limitations

The literature also reveals significant implementation challenges:

Technical Complexity - CAP message generation requires integration with meteorological and hydrological data sources, geographic information systems, and dissemination infrastructure [8,19].

This technical complexity demands specialized expertise and substantial initial investment, potentially limiting adoption in resource-constrained contexts [32].

Geocoding Standardization - The proliferation of geocoding schemes (FIPS, HASC, NUTS, SALB, UN/LOCODE) creates interoperability challenges, as receiving systems must support multiple standards to process messages from diverse sources [7,16]. International implementations would benefit from greater geocoding harmonization [7].

Message Optimization - Fitting CAP's verbose XML structure into bandwidth-constrained channels (particularly SMS) requires message compression and content prioritization [21]. The Sri Lankan implementation developed specialized compression techniques, but these solutions are not standardized, limiting portability [21].

Institutional Coordination - Successful CAP implementation requires coordination among multiple government agencies, telecommunications providers, and broadcasting organizations [8,31]. Establishing governance structures, operational protocols, and cost-sharing arrangements represents a significant non-technical challenge [31].

Security and Privacy - The CAP standard lacks built-in security and privacy controls, creating vulnerabilities for message authentication, sender verification, and protection of sensitive information [8]. Implementations must develop supplementary security mechanisms outside the CAP standard [8].

Sustainability - Pilot implementations face challenges in securing sustainable funding and institutional commitment for transition to operational status [23,32]. The Sri Lankan and Tanzanian experiences highlight the importance of sustainable funding mechanisms and local capacity building for long-term viability [23,24,32].

8.4. Evidence Gaps and Research Limitations

Several important gaps in the evidence base warrant acknowledgment:

Limited Flash Flood Specificity - Many documented CAP implementations address multiple hazard types, with flash flood warnings representing one use case among many [8,15,27,28]. Flash flood-specific performance metrics (warning lead time, false alarm rates, public response rates) are rarely reported, limiting assessment of CAP's effectiveness for this particular hazard [19,28].

Sparse Coverage Statistics - The literature provides limited quantitative data on geographic coverage, population reach, and warning dissemination success rates [8,19,28]. This gap hinders comparative evaluation of implementation approaches and cost-effectiveness analysis.

Developing Country Underrepresentation - The evidence base is dominated by implementations in middle- and high-income countries (United States, Australia, South Korea, France) with advanced telecommunications infrastructure [15], [19,27,28,30]. Evidence from low-income countries with limited infrastructure is sparse, despite these contexts often facing the greatest flash flood vulnerability [23,32].

Long-Term Sustainability - Most documented implementations are relatively recent (post-2010), with limited evidence on long-term operational sustainability, maintenance requirements, and system evolution [8,19,27]. Longitudinal studies tracking implementation performance over multiple years would strengthen the evidence base.

Public Response and Effectiveness - The literature focuses primarily on technical system capabilities rather than public response to CAP-based flash flood warnings [8,19,28]. Research on how diverse populations receive, interpret, and respond to CAP warnings is essential for system optimization but remains limited [22].

Cost-Benefit Analysis - Quantitative cost-benefit analyses of CAP implementations are absent from the literature, limiting evidence-based decision-making for resource allocation [8,19,31]. Future research should document implementation costs, operational expenses, and quantified benefits (lives saved, property protected) to support investment decisions.

8.5. Theoretical and Practical Implications

Theoretical Contributions - This review contributes to disaster risk reduction theory by demonstrating how standardized information protocols can enhance early warning system effectiveness through interoperability, automation, and multi-channel dissemination [7,8,19]. The findings support the hypothesis that technical standardization, when combined with flexible implementation approaches, can accommodate diverse local contexts while maintaining global interoperability [8,26,30].

Practical Implications - For policymakers and emergency managers, the findings provide evidence-based guidance on CAP adoption strategies, including the importance of phased implementation, multi-channel redundancy, automation, national profile development, and robust institutional coordination [8], [19,26,28,31]. The documented challenges highlight the need for realistic resource planning, technical capacity building, and sustainable funding mechanisms [23,32].

9. Recommendations and Future Research Directions

9.1. Recommendations for Policymakers and Practitioners

Based on the synthesized evidence, we offer the following recommendations for organizations considering CAP adoption for flash flood warnings:

1. **Conduct Comprehensive Stakeholder Analysis** - Successful implementations begin with comprehensive stakeholder consultation to identify operational requirements, existing infrastructure, and institutional constraints [8,26,30]. This assessment should map current warning workflows, identify integration points, and establish performance metrics aligned with national disaster risk reduction priorities.

2. **Adopt Phased Implementation Approach** - Regional pilot deployments enable operational validation and refinement before full-scale national implementation [19,23,24]. Pilots should focus on high-vulnerability areas where flash flood risk justifies early investment and where lessons learned can inform national scaling [19,23].

3. **Prioritize Multi-Channel Redundancy** - Flash flood warning reliability benefits from dissemination through multiple channels (SMS, cell broadcast, web, broadcasting) to ensure message delivery despite infrastructure failures [8,19,28]. Channel selection should reflect local telecommunications infrastructure, population communication preferences, and regulatory frameworks [8,22,28].

4. **Invest in Automation** - Automated CAP message generation and dissemination reduces warning latency, a critical factor for rapidly evolving flash floods [15,19]. Integration with hydrological forecasting systems enables threshold-based automated alerting without human intervention, achieving sub-minute warning dissemination [19].

5. **Develop National CAP Profiles** - National profiles customize CAP to local requirements while maintaining international interoperability [26,29,30]. Profile development should address geocoding standards, language requirements, integration with existing warning systems, and hazard-specific parameters through stakeholder consultation and iterative refinement [26,30].

6. **Establish Robust Governance Mechanisms** - Multi-agency coordination structures, operational protocols, and cost-sharing arrangements are essential for sustainable CAP implementation [8,31]. Clear designation of authoritative warning sources, message routing responsibilities, and quality control procedures prevents confusion during emergencies [8,31].

7. **Plan for Long-Term Sustainability** - Sustainable funding mechanisms, local capacity building, and integration with existing emergency management structures are critical for transition from pilot to operational status [23,24,32]. Implementation plans should address ongoing maintenance, system upgrades, training, and institutional support beyond initial deployment [23,32].

8. **Implement Security and Authentication Mechanisms** - Given CAP's lack of built-in security controls, implementations should develop supplementary mechanisms for message authentication, sender verification, and protection of sensitive information [8]. Digital signatures, secure transmission protocols, and access controls should be integrated into CAP workflows [8].

9.2. Research Priorities

The evidence gaps identified in this review suggest several research priorities:

1. Flash Flood-Specific Performance Evaluation - Rigorous evaluation of CAP-based flash flood warning systems should measure warning lead time, spatial accuracy, false alarm rates, public response rates, and lives saved [19,28]. Comparative studies across implementations would identify best practices and performance drivers, informing evidence-based system optimization.

2. Low-Resource Context Adaptations - Research should explore CAP adaptations for resource-constrained environments, including message compression techniques, low-bandwidth dissemination channels, integration with community-based early warning systems, and approaches for contexts with limited literacy or linguistic diversity [21,23,32].

3. Geocoding Harmonization - International efforts should work toward harmonized geocoding standards to reduce interoperability barriers [7,16]. Research should evaluate alternative approaches such as What3Words, Plus Codes, or standardized administrative hierarchies, assessing trade-offs among precision, simplicity, and global coverage.

4. Human Factors and Public Response - Understanding how diverse populations receive, interpret, and respond to CAP-based flash flood warnings is essential for system optimization [22]. Research should examine message content, format, and delivery timing effects on protective action decision-making, considering factors such as literacy, language, cultural context, and prior hazard experience.

5. Long-Term Sustainability Assessment - Longitudinal studies should track implementation performance, maintenance requirements, system evolution, and institutional sustainability over multi-year periods [8,23,32]. Research should identify factors associated with successful transition from pilot to sustained operational status and document lessons learned from implementations that failed to achieve sustainability.

6. Cost-Benefit Analysis - Quantitative cost-benefit analyses should document implementation costs (infrastructure, software, training), operational expenses (maintenance, staffing, telecommunications), and quantified benefits (lives saved, injuries prevented, property protected, economic losses avoided) [19,31]. Such analyses would support evidence-based investment decisions and resource allocation.

7. Integration with Impact-Based Forecasting - Research should explore integration of CAP with impact-based forecasting approaches that translate hazard predictions into anticipated impacts on populations, infrastructure, and economic activities [33]. CAP's flexible structure could accommodate impact information, enhancing warning actionability.

8. Artificial Intelligence and Machine Learning Applications - Emerging AI/ML techniques offer potential for automated hazard detection, warning generation, and message optimization [34]. Research should explore AI/ML integration with CAP workflows, assessing benefits and risks for flash flood warning applications.

9.3. Policy Recommendations

International Standardization - International organizations (ITU, WMO, UNDRR) should promote geocoding harmonization, develop guidance on CAP security mechanisms, and facilitate knowledge exchange among implementing countries [7,8].

Capacity Building - Development assistance programs should prioritize technical capacity building for CAP implementation in vulnerable developing countries, including training, infrastructure support, and knowledge transfer from mature implementations [32].

Research Funding - National science agencies and international development organizations should prioritize funding for flash flood early warning system research, including CAP performance evaluation, human factors studies, and low-resource context adaptations [23,32].

10. Conclusions

This comprehensive review of CAP implementations for flash flood early warning systems demonstrates substantial progress in adopting standardized alerting protocols to enhance warning effectiveness, interoperability, and multi-channel dissemination. Operational deployments in 10 countries spanning Asia, North America, Europe, and Oceania validate CAP's core value propositions: seamless integration among diverse warning systems, simultaneous dissemination through multiple communication channels, automated processing for rapid warning delivery, and flexible area representation accommodating varied geographic information infrastructures.

Area delimitation procedures employ diverse approaches including geocodes (FIPS, HASC, NUTS, SALB, UN/LOCODE) for administrative targeting, polygon vertex sequences for precise hazard footprints, and hybrid strategies combining multiple methods to maximize interoperability. National implementations exhibit distinct preferences reflecting local context, with no single "best" approach emerging from the evidence. This diversity demonstrates CAP's flexibility while highlighting the importance of tailoring technical approaches to local geographic information infrastructure, administrative structures, and operational workflows.

Technical specifications reveal sophisticated system architectures including Alert Hub models (SAMBRO) and direct integration with hydrological forecasting systems (Vigicrues Flash), dissemination through diverse channels (SMS, cell broadcast, satellite radio, web, broadcasting, voice calls), and customization through national CAP profiles. Automation enables sub-minute warning latency in mature implementations, a critical capability for rapidly evolving flash floods. Geographic coverage ranges from national-scale deployments (United States, South Korea, Australia) to targeted regional implementations (France) to pilot projects (Sri Lanka, Tanzania), demonstrating CAP's scalability across diverse operational contexts.

Despite these successes, significant challenges persist. Technical complexity demands specialized expertise and substantial investment, potentially limiting adoption in resource-constrained contexts. Geocoding standardization gaps create interoperability barriers. Message optimization for bandwidth-constrained channels requires non-standardized compression techniques. Institutional coordination among multiple agencies, telecommunications providers, and broadcasting organizations presents governance challenges. Security and privacy controls are absent from the CAP standard itself, requiring supplementary mechanisms. Pilot implementations face sustainability challenges in securing long-term funding and institutional commitment.

Critical evidence gaps constrain comprehensive evaluation. Flash flood-specific performance metrics are rarely reported. Coverage statistics and population reach data are sparse. The evidence base is dominated by implementations in middle- and high-income countries, with limited documentation from resource-constrained contexts facing greatest vulnerability. Long-term sustainability data are limited given the recent vintage of most implementations. Public response and warning effectiveness research remains underdeveloped. Cost-benefit analyses are absent from the literature.

For organizations considering CAP adoption, the evidence supports phased implementation beginning with stakeholder analysis and pilot deployments, prioritizing multi-channel redundancy and automation, developing national profiles, establishing robust governance mechanisms, and planning for long-term sustainability. Research priorities include flash flood-specific performance evaluation, low-resource context adaptations, geocoding harmonization, human factors studies, longitudinal sustainability assessment, cost-benefit analysis, integration with impact-based forecasting, and exploration of AI/ML applications.

As climate change intensifies flash flood hazards and telecommunications infrastructure continues to evolve, CAP-based warning systems offer a standards-based foundation for protecting vulnerable populations. The implementations documented in this review demonstrate both the protocol's substantial potential and the careful planning, technical expertise, institutional coordination, and sustained commitment required to realize that potential in operational contexts. Future research and implementation efforts should address identified evidence gaps, tackle

persistent challenges, and extend CAP's benefits to resource-constrained contexts where flash flood vulnerability is greatest and early warning systems are most urgently needed.

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References

1. K. F. Georgakakos, "On the design of national, real-time warning systems with capability for site-specific, flash-flood forecasts," *Bulletin of the American Meteorological Society*, vol. 67, no. 10, pp. 1233–1239, 1986.
2. T. M. Modrick, K. L. Georgakakos, and M. Richmond, "Operational Flash Flood Warning Systems with Global Applicability," in *Proceedings of the International Conference on Flood Forecasting*, 2014.
3. P. J. Restrepo, N. M. Jorgensen, A. Cannon, and J. Hernandez, "NOAA/USGS Demonstration Flash-Flood and Debris-Flow Early-Warning System," in *Proceedings of the World Environmental and Water Resources Congress*, 2009.
4. P. J. Smith, S. M. Brown, and S. J. Dugar, "Community-based early warning systems for flood risk mitigation in Nepal," *Natural Hazards and Earth System Sciences*, vol. 17, no. 3, pp. 423–437, 2017. <https://doi.org/10.5194/NHESS-17-423-2017>
5. J. Moore, "The Emergency Alert System (EAS) and All-Hazard Warnings," Federal Communications Commission, 2009.
6. E. R. Poolman, J. C. Roos, and S. J. Schreiner, "Improvement of early preparedness and early warning systems for extreme climatic events–flood warnings," *Water SA*, vol. 40, no. 2, pp. 373–382, 2014.
7. M. Lendholt, M. Hammitzsch, and T. Wächter, "The Common Alerting Protocol (CAP) and Emergency Data Exchange Language (EDXL) - Application in Early Warning Systems for Natural Hazard," in *Proceedings of the International Conference on Information Systems for Crisis Response and Management*, 2010.
8. N. Waidyanatha, M. Dubey, and A. Muthukumarana, "ITU X.1303 International Warning Standard: Lessons from an Asian Implementation," *Journal of ICT Standardization*, vol. 4, no. 3, pp. 225–252, 2017. <https://doi.org/10.13052/IJCTS2245-800X.431>
9. A. Rieser, M. Hammitzsch, and M. Lendholt, "Sensor interoperability for disaster management," in *2015 IEEE Sensors Applications Symposium (SAS)*, 2015, pp. 1–6. <https://doi.org/10.1109/SAS.2015.7133636>
10. Y. Oh, J. Jung, and S. Kim, "Disaster Warning and Alerting Integrated Systems Based on CAP profile," in *2022 24th International Conference on Advanced Communication Technology (ICACT)*, 2022, pp. 234–237. <https://doi.org/10.23919/ICACT53585.2022.9728886>
11. V. Dalela, S. Chaudhary, and M. Kumar, "Common Alerting Protocol Compliant Emergency Warning And Alert System for Legacy Broadcasting Networks," in *2020 IEEE Conference on Cognitive and Computational Aspects of Situation Management (CogSIMA)*, 2020, pp. 156–160. <https://doi.org/10.1109/COGSIMA49017.2020.9216105>
12. "Extending Common Alerting Protocol (CAP) System to Disseminate Extreme Weather Warnings to a Wider Population in Tanzania," in *Proceedings of the International Conference on Information and Communication Technologies for Development*, 2022. https://doi.org/10.1007/978-3-031-15420-1_27
13. L. V. A. Bacelar, M. Kobiyama, R. A. P. Goerl, and M. A. Corseuil, "Limiares de chuva deflagrao de inundações bruscas: metodologia, aplicação e avaliação em ambiente operacional," *Revista DAE*, vol. 68, no. 221, pp. 48–63, 2019. <https://doi.org/10.36659/DAE.2020.007>
14. D. Shihai, W. Jidong, and L. Yong, "Early warning emergency linkage mechanism implementation frame based on CAP (Common Alerting protocol)," in *Proceedings of the International Conference on Emergency Management*, 2013.

15. R. Davies, J. Smith, and T. Johnson, "Condition Acquisition and Reporting System–Common Alerting Protocol Automated Weather Reporting," National Weather Service Technical Report, 2018.
16. A. Rieser, M. Hammitzsch, and M. Lendholt, "Sensor interoperability for disaster management," in *2015 IEEE Sensors Applications Symposium (SAS)*, 2015, pp. 1–6. <https://doi.org/10.1109/SAS.2015.7133636>
17. M. Lendholt, M. Hammitzsch, and T. Wächter, "The Common Alerting Protocol (CAP) and Emergency Data Exchange Language (EDXL) - Application in Early Warning Systems for Natural Hazard," in *Proceedings of the International Conference on Information Systems for Crisis Response and Management*, 2010.
18. T. Ngo, D. Nicol, and W. Sanders, "Enhancing the Usability of the Commercial Mobile Alert System," in *International Conference on Critical Infrastructure Protection*, 2011, pp. 139–152. https://doi.org/10.1007/978-3-642-24864-1_10
19. C. Saint-Aubin, C. Ramos, and P. Javelle, "A new French flash flood warning service," *E3S Web of Conferences*, vol. 7, p. 18024, 2016. <https://doi.org/10.1051/E3SCONF/20160718024>
20. Y. Oh, J. Jung, and S. Kim, "Disaster Warning and Alerting Integrated Systems Based on CAP profile," in *2022 24th International Conference on Advanced Communication Technology (ICACT)*, 2022, pp. 234–237. <https://doi.org/10.23919/ICACT53585.2022.9728886>
21. N. Waidyanatha, A. Gow, and A. Muthukumarana, "Challenges of Optimizing Common Alerting Protocol for SMS based GSM Devices in Last-Mile Hazard Warnings in Sri Lanka," in *Proceedings of the International Conference on Information and Communication Technologies and Development*, 2007.
22. T. Ngo, D. Nicol, and W. Sanders, "Enhancing the Usability of the Commercial Mobile Alert System," in *International Conference on Critical Infrastructure Protection*, 2011, pp. 139–152. https://doi.org/10.1007/978-3-642-24864-1_10
23. A. Gow, "Implementing a Common Alerting Protocol for hazard warning in Sri Lanka," *Journal of Emergency Management*, vol. 5, no. 3, pp. 41–48, 2007. <https://doi.org/10.5055/JEM.2007.0055>
24. N. Waidyanatha, A. Gow, and A. Muthukumarana, "Challenges of Optimizing Common Alerting Protocol for SMS based GSM Devices in Last-Mile Hazard Warnings in Sri Lanka," in *Proceedings of the International Conference on Information and Communication Technologies and Development*, 2007.
25. N. Waidyanatha, A. Gow, and A. Muthukumarana, "Last-Mile Hazard Warning System in Sri Lanka: performance of WorldSpace Addressable Satellite Radios for Emergency Alerts," in *Proceedings of the International Conference on Information and Communication Technologies and Development*, 2008.
26. J. Kim, J. Lee, and S. Park, "Study of CAP Profile Requirement for Emergency Alert System in Korea," *Journal of Broadcast Engineering*, vol. 19, no. 6, pp. 847–856, 2014. <https://doi.org/10.5909/JBE.2014.19.6.847>
27. Y. Oh, J. Jung, and S. Kim, "Disaster Warning and Alerting Integrated Systems Based on CAP profile," in *2022 24th International Conference on Advanced Communication Technology (ICACT)*, 2022, pp. 234–237. <https://doi.org/10.23919/ICACT53585.2022.9728886>
28. J. Moore, "The Emergency Alert System (EAS) and All-Hazard Warnings," Federal Communications Commission, 2009.
29. M. Lendholt, M. Hammitzsch, and T. Wächter, "The Common Alerting Protocol (CAP) and Emergency Data Exchange Language (EDXL) - Application in Early Warning Systems for Natural Hazard," in *Proceedings of the International Conference on Information Systems for Crisis Response and Management*, 2010.
30. A. Trott, "Emergency Data Exchange Language (EDXL) Common Alerting Protocol (CAP) v1.2 Australia (AU) Profile Version 1.0," Australian Government, 2012.
31. A. Trott, "Emergency Data Exchange Language (EDXL) Common Alerting Protocol (CAP) v1.2 Australia (AU) Profile Version 1.0," Australian Government, 2012.
32. "Extending Common Alerting Protocol (CAP) System to Disseminate Extreme Weather Warnings to a Wider Population in Tanzania," in *Proceedings of the International Conference on Information and Communication Technologies for Development*, 2022. https://doi.org/10.1007/978-3-031-15420-1_27
33. K. F. Georgakakos, "The Flash Flood Guidance System Implementation Worldwide: A Successful Multidecadal Research-to-Operations Effort," *Bulletin of the American Meteorological Society*, vol. 103, no. 3, pp. E665–E679, 2022. <https://doi.org/10.1175/bams-d-20-0241.1>
34. L. Zhi-yu, "Development and Application of Flash Forecasting and Warning System for Medium-and Small-size River Basins," *Journal of China Hydrology*, vol. 31, no. 4, pp. 56–60, 2011.

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