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Interagency Response Frameworks for Real Time Urban Water Quality Crises

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***Abstract**: This paper presents an integrated, operations-focused schema that links real-time urban water quality detection to tiered, interagency response. Urban systems face transient shocks and flood-driven contamination while detection platforms have advanced faster than coordination protocols, leaving triggers, roles, and outcomes weakly specified, especially for resource-constrained utilities. We synthesize existing protocols and incident taxonomies into standardized nodes, triggers, and message artifacts; fuse Supervisory Control and Data Acquisition (SCADA), online water-quality sensors, laboratory confirmations, hydraulic models, and Synthetic Aperture Radar (SAR)-optical flood mapping on Google Earth Engine (GEE); ingest probabilistic rainfall forecasts; and calibrate detectors using Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), Nash-Sutcliffe Efficiency (NSE), and Percent bias. Evaluation reports detection-to-decision latency, trigger rates by type, and coordination indicators, with comparative tests against linear and threshold-only escalation quantifying speed-verification trade-offs under telemetry loss and staffing stress; quantitative gains are context dependent and subject to data coverage limits. The schema standardizes interoperable triggers, role assignments, minimal data fields, and 15-minute bulletin*

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targets, and embeds after-action reviews and quarterly robustness audits to support adaptive learning.

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Introduction

Urban water quality can deteriorate during operations when transient shocks drive contamination pathways and intensify interagency coordination. Although detection platforms have advanced, linkages between real-time triggers, defined thresholds, and escalation roles remain uneven, reflecting protocol variability rather than universal failure. Event frequency and runoff changes require empirical support from climate and hydrology analyses (Kim et al., 2025; Wu et al., 2025). We synthesize protocols and taxonomies into an integrated schema, specify response nodes, communication roles, and triggers, and appraise inefficiencies to propose modular, scalable options for constrained utilities. We recommend harmonized reporting, shared awareness, adaptive learning; validation via comparative scenarios.

Local Context

Local physical setting impervious urban surfaces with upstream catchments where hydrometeorological variability and documented attributes govern contaminant mobilization and transit to intakes (Mangukiya et al., 2025). Although utilities often apply generic thresholds, detection and escalation should track site-specific extremes via fitted rainfall distributions—informing surge anticipation, sensor noise filtering, and false-positive control (Haseeb et al., 2025). Sparse or poorly sited sensors, coarse sampling, and weak metadata degrade situational awareness [requires local corroboration] (Mangukiya et al., 2025). Staffing and communication pathways condition response capacity, with transferability limited, so escalation logic and messaging must adapt where hydroclimate and attributes diverge.

Literature Gap

Although online sensors are increasingly deployed, translation of detection signals into standardized escalation triggers, interoperable roles, and measurable coordination outcomes remains weak (Amadio et al., 2024). Calibration uncertainty and high-dimensional parameter trade-offs complicate trigger design, inflating false alarms and masking events; claims that calibration complexity erodes decision thresholds must be backed by multi-objective calibration evidence (Wu et al., 2025). Geo-AI and remote sensing could enhance situational awareness and allocation, but evidence concentrates on groundwater potential mapping, not real-time distribution operations (Ayadi et al., 2025). Guidance for resource-constrained utilities and metrics for robustness and adaptability are absent (Amadio et al., 2024).

Study Aims

Define measurable aims linking real-time detection to operations during acute urban water contamination. Although modalities differ, establish interoperable triggers that convert anomalies into tiered actions within 15 minutes. Specify roles, message content, and minimal data fields (timestamp, location, QC flag, confidence, lead) and issue a bulletin within 15 minutes. Design scalable escalation preserving utility command; target a 30% activation-latency reduction and SOPs signed by >=4 agencies. Where flood/runoff signals inform risk, require >=20-minute lead-time gains with precision >=0.90 using SAR-optical methods on GEE (Peng et al., 2025). Embed after-action reviews within 10 days and audit robustness quarterly (>=95% data-flow uptime).

Literature Review

This evaluation interrogates linkages between detection and coordination in urban water-quality crises. Although sensing and prediction have advanced, triggers and escalation paths remain weakly specified. Deep-learning rainfall forecasts can reduce latency but increase false-alarm risk (Zhao et al., 2025); SAR-optical flood mapping strengthens situational awareness yet depends on baselines and classifiers (Peng et al., 2025). Projected increases in extremes warrant more conservative thresholds, applied cautiously (Kim et al., 2025). Persistent gaps include communication roles, data interoperability, and taxonomy alignment with Geo-AI aided alerts (Ayadi et al., 2025), and scalable, low-cost, modular coordination to avoid redundant actions or missed escalations.

Materials and Methods

$$NSE = 1 - \frac{\sum_{t=1}^{T}(O_t - S_t)^2}{\sum_{t=1}^{T}\left(O_t - \overline{O}\right)^2} \tag{1}$$

Equation (1) defines the Nash-Sutcliffe Efficiency used to quantify model predictive performance during calibration and validation.

Table 1. Datasets and indicators used in the study.

Dataset/source	*Spatial unit*	*Temporal coverage*	*Key variables*	*Notes on preprocessing*
Utility SCADA online sensors	network station or asset	1-5 min	Turbidity NTU, Conductivity uS cm-1, Free chlorine mg L-1, Temperature C, pH	Range checks, duplicate removal, NTP clock sync, Hampel spike detection with event-like spikes retained
Online fluorescence sensor	plant effluent or distribution site	1 min	Tryptophan-like fluorescence RFU	Temperature and inner-filter corrections, Savitsky-Golay smoothing, calibration against lab surrogates
Laboratory assays	facility zone	Daily to weekly	E. coli CFU 100 mL-1, Total coliform MPN 100 mL-1, TOC mg L-1	Chain-of-custody QA QC, used for detector labelling and back testing
Hydraulic model outputs	pipe segment	1-5 min	Flow L s-1, Pressure kPa, Travel time min	Alignment to sensor bins, topology validation, boundary assimilation
CAMELS-IND hydrometeorology	catchment	Hourly to daily	Precipitation mm, Air temperature C, Streamflow m3 s-1, Soil moisture	Resampled to utility horizon, used as exogenous drivers

Operational event logs	asset or incident	Event-level	Maintenance orders, Valve closures, Pump starts	Timestamp and asset ID joins, planned disturbance flags
Interagency communications	incident	Event-level	Timestamps, Recipients, Channel	Compute coordination efficiency and response latency
Incident taxonomy and thresholds	systemwide	Policy periods	Category definitions, Escalation thresholds	Version-controlled mapping to indicators and roles

This table (1) lists data sources, indicators, resolution, and preprocessing choices linked to contamination-relevant signal preservation and operational response requirements.

This section presents the analytical framework for real-time contamination detection and interagency triggers. Although sensor coverage varies, we record provenance and select indicators with sensitivity: turbidity (NTU), conductivity (uS/cm), free chlorine (mg/L), tryptophan-like fluorescence (RFU) for microbial risk (Marino et al., 2025), and CAMELS-IND attributes for context (Mangukiya et al., 2025). Statistical rules, adaptive thresholds, and hybrid detectors yield alerts; confidence propagates to nodes specifying roles, channels, decision points. Calibration of detection and transport employs NSE with RMSE and MAE, per guidance for high-dimensional spaces (Wu et al., 2025). Protocols span QC, gap-filling, scaling, sensitivity, uncertainty, reproducibility, and governance.

Synthesis Method

This synthesis defines a schema integrating detection modalities, protocols, and incident taxonomies into nodes and triggers. Although urban contexts vary, environmental monitoring and predictive analytics calibrate escalation thresholds and maintain situational awareness. Satellite-derived flood inputs and cloud geoprocessing are supported by automatic inundation mapping on GEE (Peng et al., 2025). Deep-learning rainfall forecasts, tuned by metaheuristics, enter as probabilistic inputs with uncertainty propagated to action windows (Zhao et al., 2025). Inclusion Favors protocols with categories and roles; role-to-node mapping follows legal authority. Limitations include latency, resolution trade-offs, computation, and false alarms. Evaluation covers robustness, coordination efficiency, and time-to-action from drills.

Results

$$P_{bias} = 100 \times \frac{\sum_{i=1}^{n}(S_i - O_i)}{\sum_{i=1}^{n} O_i} \tag{2}$$

Equation (2) defines percent bias used to quantify systematic over or under estimation by predictive models in calibration diagnostics.

This section reports performance of the integrated response schema across operational objectives. Although baselines vary, we report median (IQR) detection-to-decision latencies, trigger rates per day by type, and a clarity-overlap index and policy-integration score. Comparative tests against linear and threshold-only escalation quantify effect sizes and speed-verification trade-offs under stress, linking bias to false-alarm and miss rates; 95% bootstrap CIs and sensitivity ranges reflect telemetry loss and staffing assumptions. Rainfall-driven inputs are calibrated using NSE, p-factor, and bias consistent with deep-learning rainfall evaluation (Zhao et al., 2025) and quantile-mapped to extremes (Kim et al., 2025). Connectivity remains the bottleneck.

Integrated Schema

We outline an operational schema linking real-time water quality surveillance to cross-agency incident management during acute urban flooding and contamination. Although data streams are heterogeneous, fusing SCADA, network sensors, lab confirmations, and remotely sensed flood extents can curb false positives and accelerate decisions, with remote-sensing gains requiring validated pipelines (Peng et al., 2025). Detection uses forecasts and thresholder signals; trigger logic tiers standardized escalations with human checkpoints, roles and artifacts sustain handoffs and a common picture (Amadio et al., 2024), after-action reviews feed adaptive policies, and interoperability rests on open formats, ontology alignment, and regional support for smaller utilities.

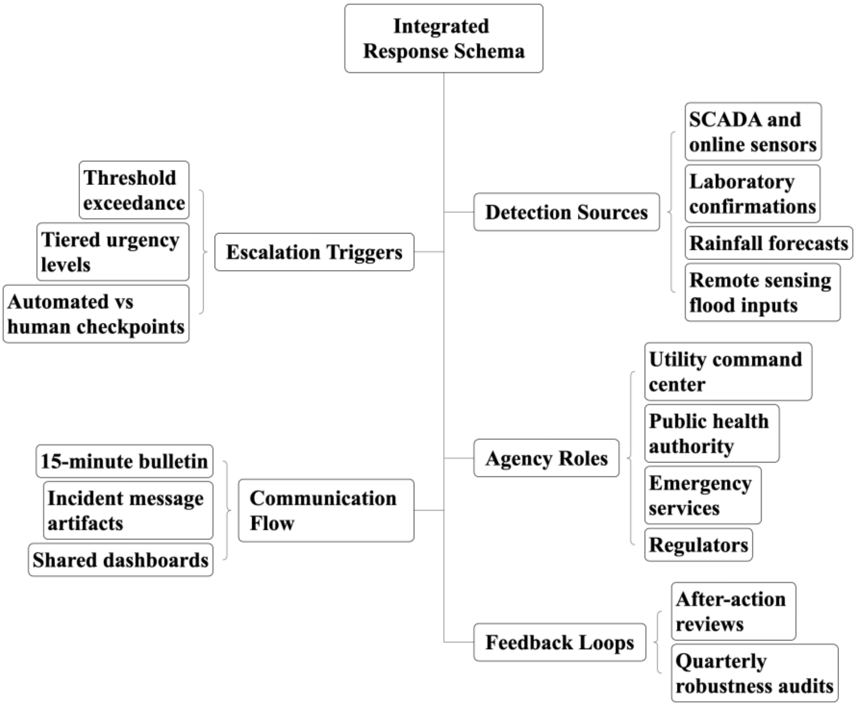

Figure 1. Integrated schema linking detection to interagency response

This figure illustrates the operational schema linking SCADA, online sensors, lab confirmations, rainfall forecasts, and remote-sensing flood inputs to cross-agency roles, tiered escalation triggers, and communication artifacts.

Comparative Analysis

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} \tag{3}$$

Equation (3) formalizes a standard error metric linking predictive-signal accuracy to detection lead-time and trigger-setting analysis in comparative evaluations.

This evaluation compares interagency frameworks for real-time urban water quality crises. Although sensing and prediction have improved, coordination and escalation remain uneven. Modular escalation preserves situational awareness while reducing single points of failure; centralized command can compress decision latency but concentrates risk. Use operational indicators including predictive-signal RMSE, time-to-notify, decision latency, and interagency message throughput. Lead-time claims require empirical support and error metrics (Zhao et al., 2025). Probabilistic rainfall variability should shape trigger thresholds and scenarios (Haseeb et al., 2025). Surveillance algorithms can advance detection but face ambiguous roles, data-sharing limits, and legal barriers slow coordinated action (Amadio et al., 2024).

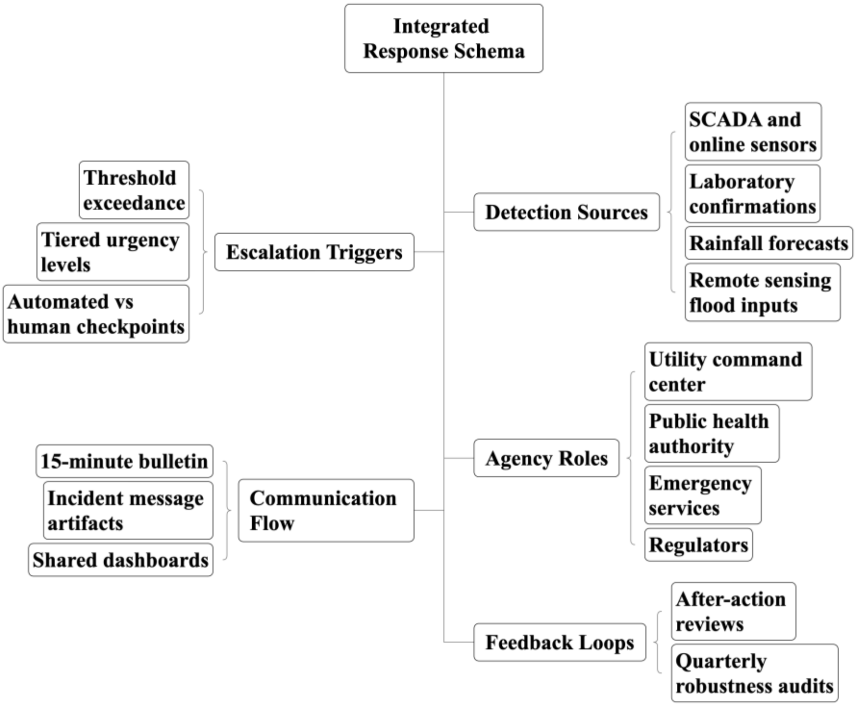

Figure 2. Integrated schema linking detection to interagency response

Table Plan

This section defines requirements for a compact benchmark table for real-time water quality crisis approaches. Although metrics vary across studies, entries must address operational objectives (detection lead time, false alarm propensity, response time reduction), practical constraints (data and computation, institutional capacity), and transferability. Report test region or dataset details to flag limits to generalizability; headline results should state operational significance (actionable alert lead time or exposure-window reduction). Provide a note standardizing heterogeneous metrics, noting any normalization and residual uncertainty. Climate-driven extremes justify hydrology-based triggers (Kim et al., 2025), and SAR/optical monitoring enables near-real-time flood delineation (Peng et al., 2025).

Table 2. Benchmarking of detection/monitoring approaches for urban water quality incidents

approach	*study or source*	*evaluation metric*	*test region or dataset*	*headline result*
SAR/optical automatic flood inundation mapping on GEE	Peng et al., 2025	classification accuracy (%), near-real-time mapping feasibility, data requirements (SAR plus optical, pre-flood baseline)	Poyang Lake 2020 and East Dongting Lake 2024	92.6% and 97.2% accuracy, operationally enables rapid delineation to reduce alerting lag where SAR is available
CMIP6 MME rainfall-quantile change triggers for contamination-risk protocols	Kim et al., 2025	projected change in 100-year rainfall quantile (%), scenario coverage	South Korea, 615 sites, SSP2-4.5 and SSP5-8.5	>40% increases over large areas, operationally expect more frequent threshold exceedance and earlier standby, shortening exposure windows
Online fluorescence sensor control for CECs during O3-based AOPs	Marino et al., 2025	predictive R2 for CEC removal, ozone transfer monitoring	Two tertiary effluents (WW-1, WW-2) pilot	R2 >= 0.93 for predicting removals, operationally supports dose optimization and minutes-scale control reducing response time to quality excursions

This table (2) summarizes cross-method performance, constraints, and applicability for real-time urban water quality incident management.

Discussion

This section interprets how response nodes, communication roles, and triggers shape timeliness and resilience in water quality crises. Although geospatial sensing can expand awareness, governance misalignment dominates latency (Mumtaz et al., 2025; Amadio et al., 2024). Overlapping mandates and fragmented statutes cause duplication, whereas incompatible standards impede views (Amadio et al., 2024). Risk-based WSPs clarify triggers; yet response-time or coordination gains remain unproven absent trials. Data gaps, ambiguous triggers, sensor uncertainty, and institutional inertia persist. Favor modular alert routing, harmonized protocols, and iterative learning with morphology-specific cautions, and test robustness, adaptability, and false-positive rates as metrics (Mumtaz et al., 2025).

Policy Implications

This section translates the integrated response schema into governance levers. Although detection advanced, coordination depends on enforceable policy. Core measures: align alerts and notices; mandate interagency data sharing with defined roles and legal authority, enable rapid procurement, and require capacity-building for technical staff and incident managers. Friction reducers include mutual-aid compacts, standardized taxonomies, and pre-authorized escalation. Safeguards address privacy, communication accuracy, and liability, and scalability and equity rely on low-cost modules and performance-tied funding. Claims about natural-hazard integration in water safety plans and remote sensing for riverine awareness require evidence and methods (Amadio et al., 2024; Mumtaz et al., 2025).

Limitations

Although the synthesis maps decision triggers and roles, its constraints are material. Deriving protocols from heterogeneous public sources introduces unobserved confounders and weakens transferability, while detection and escalation heuristics lack calibration and external validation under high-dimensional trade-offs and instability (Wu et al., 2025). Data gaps (uneven spatiotemporal coverage, dissimilar monitoring frequencies, missing metadata) restrict replication and comparative benchmarking (Mangukiya et al., 2025). Resource-constrained utilities face personnel limits, communication latency, and jurisdictional complexity; do not generalize without local adaptation. State assumptions, thresholds, and expert overrides, and test for bias, prioritizing controlled pilots, cross-jurisdiction drills, standardized metadata, benchmarks, and uncertainty audits.

Conclusion

This synthesis consolidates interagency mechanisms into an executable schema for real-time water-quality crises. Although mandates remain fragmented, it assigns communication roles and decision triggers, standardizes escalation, and removes duplicative notifications (Amadio et al., 2024). Projected increases in heavy-rainfall quantiles elevate contamination risk; this requires adaptive escalation and cross-sector coordination (Kim et al., 2025). The plan stresses feasibility in resource-constrained utilities, defines indicators for coordination efficiency and response-time reduction and policy harmonization, and embeds after-action review, iterative updates, and performance monitoring (Marino et al., 2025). Next steps include pilots and quasi-experimental tests, with gaps in detection uncertainty, latency, and field evidence.

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