Bridging Regulatory Compliance and Real Time Water Quality Reporting for Dynamic Auditability

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Abstract: *Real-time water quality surveillance demands continuous, regulation-aligned reporting, yet legacy compliance pipelines lack interoperability, change traceability, and on-demand audit support. We propose a conceptual framework that unifies regulatory taxonomy mapping, executable compliance workflow modelling, and continuous audit trail maintenance for dynamic reporting. A comparative analysis of environmental reporting architectures and scenario-based validation indicate improved framework applicability and regulatory adaptability, with gains in compliance accuracy, reporting efficiency, and auditability via traceable change logs and schema-aligned outputs. The distinctive integration of taxonomy-driven rules with streaming audit artifacts enables first-of-its-kind dynamic auditability. This advances practical, low-risk, continuously compliant utility reporting.*

Keywords: Real-Time Surveillance, Water Quality Compliance, Regulatory Reporting, Audit Trail, Environmental Regulations, Digital Compliance

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Introduction

This paper addresses the pressures of continuous sensor-driven surveillance under evolving environmental regulations. Although utilities deploy dense telemetry, shifting thresholds, cadences, and formats outpace reporting pipelines. Local context compounds the burden: heterogeneous data, variable monitoring cadence, and multi-stakeholder accountability complicate alignment (Datta et al., 2025). Real-time reuse initiatives intensify demands (Piazza et al., 2025). We develop a framework integrating regulatory taxonomy mapping, compliance workflow modelling, and audit trails; it enables adaptive reporting without overhauls. Methods combine conceptual modelling, comparative analysis of regulatory architectures, and indicator selection. Taxonomy mapping links rules to measures, change traceability records provenance, and auditability provides machine-readable evidence.

Local Context

Although real-time surveillance is desirable, feasibility hinges on scarce resources, limited capacity, and socioeconomic constraints. In water-scarce contexts, influent variability, uneven sampling, reclaimed reuse, and energy-carbon burdens shape workflows (Duan et al., 2025; Lee et al., 2025). Connectivity remains the bottleneck. Intermittent monitoring, low throughput, and noisy data erode audit trails and complicate taxonomy mapping. The components are conventional; their orchestration is distinctive. Design should prioritize interoperability, traceability, and adaptive responses, anchored to indicators: residual disinfectant, nutrient loads, flow variability, reuse percent, energy per unit, sensor uptime, coupling carbon targets with compliance (Lee et al., 2025; Duan et al., 2025).

Literature Gap

This section clarifies unresolved needs at the compliance-monitoring interface. Although ML monitoring advances, transferability across heterogeneous sites and robustness under operational drift remain uncertain (Irwan et al., 2025); explainability for regulatory reasoning remains limited (Riyadh & Peleato, 2025). Gaps persist in regulatory taxonomy harmonization and metadata standards, blocking semantic interoperability. Weak provenance and change management for thresholds, sampling frequencies, and formats undermine auditability and legal defensibility. Governance misaligns utilities and regulators. Priorities include versioned audit trails, adaptive rule-aware workflows, standardized validation tied to regulatory outcomes, operational metrics for reporting efficiency with compliance accuracy, and provenance-rich on-demand reporting with stakeholder verifiability.

Literature Review

Real-time water quality surveillance must align with evolving regulation. Although architectures diverge, indicator and reporting choices should reflect ecosystem dynamics and institutional constraints (Jin, 2025). Spatiotemporal trade-offs require taxonomy mapping and versioned thresholds to sustain interpretability (Zhang et al., 2025). PSR-based designs demonstrate defensible indicator selection and response-layer accountability for adaptive compliance (Jin, 2025).

Regulatory Landscape

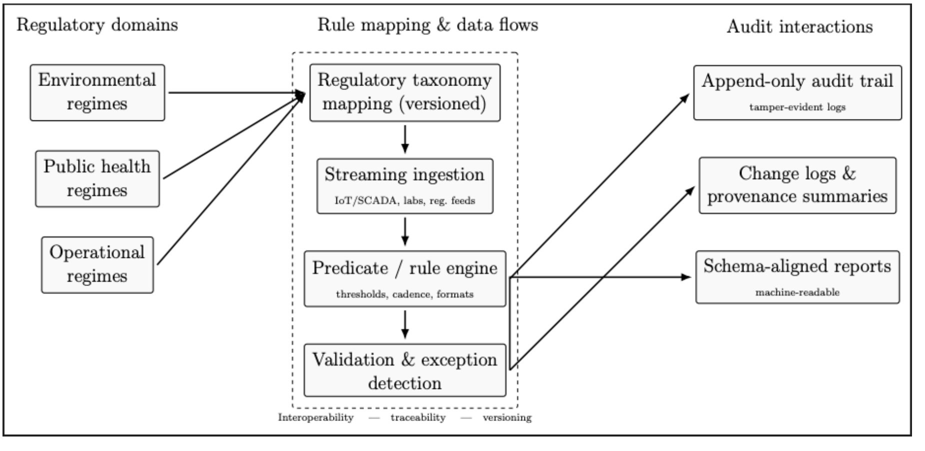

Figure 1. Regulatory domains and audit interactions overview

This figure (1) summarizes regulatory domains, data flows, and audit interactions supporting taxonomy mapping for monitoring and reporting.

Although regulatory aims converge, domain mandates diverge; environmental, public health, and operational regimes impose heterogeneous thresholds, units, frequencies and event-triggered alerts, and formats that fragment compliance. A regulatory taxonomy must encode rule logic as machine-actionable, versioned artifacts with provenance, timestamped updates, and mappings to reconcile historical data. Risk-based microbiological controls and process-water WMPs sharpen definition and thresholds (Allende et al., 2025). Municipal wastewater variability and reuse contexts illustrate monitoring burdens and constraints (Duan et al., 2025). Utilities need calibrated sensors, uncertainty propagation to decisions, exception escalation, role-based accountability, auditable metadata. Key indicators include latency, audit-trail fidelity, false alarms, amendment resilience.

Comparative Analysis

$$KGE = 1 - \sqrt{(r-1)^2 + \left(\frac{\sigma_{sim}}{\sigma_{obs}} - 1\right)^2 + \left(\frac{\mu_{sim}}{\mu_{obs}} - 1\right)^2} \quad (1)$$

Equation (1) quantifies combined correlation, variability, and bias for model-performance comparison supporting compliance accuracy and reporting efficiency assessments.

Although static, prescriptive regimes ease interpretation, they hinder continuous reporting and adaptive thresholds; performance-based regimes better support rolling thresholds, configurable alerting, and metadata governance. Interoperability suffers when heterogeneous schemas and weak provenance block automated reporting. Defensible pipelines need immutable provenance, tamper-evident logs, and versioned policy-to-data maps across threshold, cadence, and format changes. IoT-ML monitoring demonstrates responsiveness (Baena-Navarro et al., 2025), and hybrid modelling strengthens fidelity (Avila et al., 2025). Explainable attributions should be logged in audit records to justify automated decisions (Riyadh & Peleato, 2025). Comparing framework applicability, compliance accuracy, reporting efficiency, auditability, regulatory adaptability, and stakeholder satisfaction reveals gaps.

Benchmark Table

Table 1. Benchmark comparison of representative methods and domains

Method	*Domain*	*Key metric*	*Reported value*	*Notes/units*
Random Forest (IoT-ML)	Aquaculture monitoring	R2	0.999	Baena-Navarro et al., 2025
Random Forest (IoT-ML)	Aquaculture monitoring	RMSE	0.0998 mg/L	Baena-Navarro et al., 2025,

RF and LSTM	Groundwater estimation	KGE	0.6 average	Avila et al., 2025, Seine Basin
LSTM (4-layer)	Chlorine in WDS	MAE	<0.025 mg/L	Riyadh & Peleato, 2025, =
TOPSIS	Water strategy ranking	Ci+	0.640	Han et al., 2025,
TOPSIS	Water strategy ranking	Ci+	0.608	Han et al., 2025,
TOPSIS	Water strategy ranking	Ci+	0.578	Han et al., 2025,

This table (1) compiles cross-domain metrics, units, provenance, and comparability notes for regulatory benchmarking.

This guidance prioritizes cross-domain comparability and regulatory interpretability. Although metrics differ by task and design, they collectively signal accuracy, robustness, and explainability; the table should juxtapose IoT-ML aquaculture results reporting R2 and RMSE (Baena-Navarro et al., 2025), groundwater anomaly KGE from RF/LSTM (Avila et al., 2025), chlorine MAE in distribution LSTM models (Riyadh & Peleato, 2025), and decision Ci+ from TOPSIS (Han et al., 2025). Include units (mg/L for concentrations), data provenance, temporal resolution, sensor topology, and ground-truthing. Units drive regulatory interpretation. Flag heterogeneous protocols and outliers, link attributes to audit trails and compliance priorities, and press for metric standardization.

Materials Methods

This section specifies a reproducible design for real-time compliance. Although streams are volatile, inputs span electrochemical/optical sensors, lab checks, and machine-readable regulatory feeds with thresholds, dates, and jurisdictions, normalized by UTC timestamps, geotags, calibration records, loss/latency handling, anomaly flags, and imputation. A versioned taxonomy drives a predicate rule engine with escalation and auto/human reports; immutable, cryptographically checked logs support audits, and evaluation uses synthetic testbeds, replays, and regulatory-change stress with TOPSIS/FTOPSIS and DT-XAI for weighting and transparency, with governance and documented assumptions/failures, plus KPIs for accuracy, latency, responsiveness (Han et al., 2025; Erkek & Irmak, 2025).

Framework Design

$$C_i^+ = \frac{S_i^-}{S_i^+ + S_i^-} \tag{2}$$

Equation (2) defines the TOPSIS closeness coefficient for ranking alternatives using distances to positive and negative ideals.

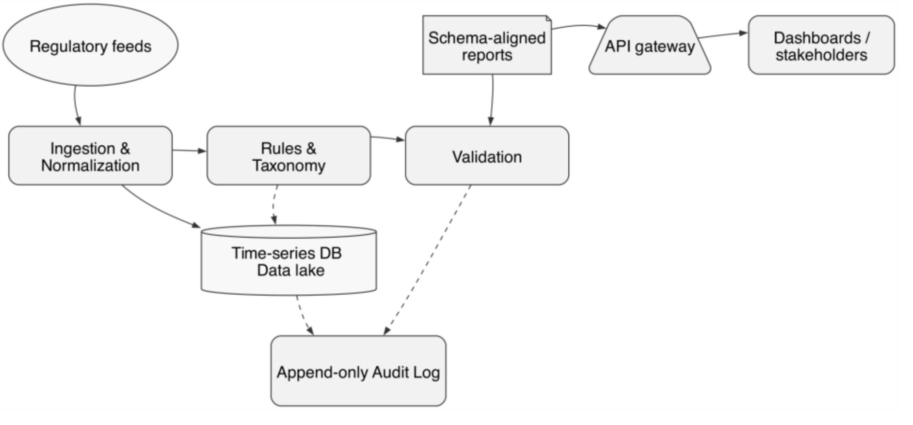

Figure 2. Proposed compliance analytics framework architecture

This figure (2) depicts components and data flows linking taxonomy mapping, streaming ingestion, adaptive rules, and audit trails for compliant operations.

This section presents an analytics model for utilities that fuses machine-interpretable regulatory taxonomies with continuous monitoring and immutable audit trails. Although regulations evolve rapidly, an adaptive rule engine and policy-change management decouple semantics from pipelines, enabling updates without redesign. Taxonomized thresholds, monitoring frequencies, and report templates drive rule-based validation, exception detection, and automated reporting and escalation. IoT and SCADA feed analytical engines for checks (Baena-Navarro et al., 2025). Provenance-rich metadata and append-only audit logs secure chain-of-custody and traceability. Interoperability relies on standardized interfaces and harmonized metadata; indicators are prioritized via TOPSIS/FTOPSIS against positive and negative ideals (Han et al., 2025).

Audit Trail

This section argues that audit trails are the backbone of real-time water quality compliance, uniting technical integrity with governance accountability. Although regulatory schemes differ, robust provenance capture, tamper-evident immutable logs, and schema-agnostic identifiers are essential to preserve temporal fidelity, sensor metadata, uncertainties, and transformation histories for defensible reconstruction (Allende et al., 2025). Authenticated access, chain-of-custody documentation, and cryptographic hashing and signatures enable non-repudiation; automated, records should expose event triggers, versioned workflows, and annotated exceptions. Retention policies, archival indexing, and provenance summaries support audits, while digital twins and explainable AI improve traceability and cybersecurity readiness (Erkek & Irmak, 2025).

Results

This section reports outcomes for the compliance audit framework. Although hydrological variability complicates signal interpretation, determinations remained stable across replayed events (Lima-Quispe et al., 2025). Scenarios covered threshold drift, cadence changes, sensor faults, missing data, and regulatory reclassification. We quantified latency, throughput, and trigger accuracy; numeric summaries are archived. Uncertainty used bootstrapping, Monte Carlo perturbations, and sensitivity indices. ML components were validated via feature importance and explainability (Riyadh & Peleato, 2025). Connectivity remains the bottleneck. We noted a trade-off between compute cost and timeliness; auditability held through event lineage. Utilities gain reduced reconciliation, evidentiary traceability, and faster regulatory adaptation.

Compliance Accuracy

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

Equation (3) quantifies the average magnitude of continuous prediction errors and supports assessment of sensor and model performance with respect to regulatory thresholds.

Compliance accuracy is measurable alignment of real-time water quality outputs with regulatory thresholds. Although hydrological variability introduces signal change and uncertainty (Lima-Quispe et al., 2025), evaluation classifies error sources: sensor noise/drift, sampling frequency and aliasing, preprocessing/aggregation bias, model structure, and threshold or labelling ambiguity. Metrics include continuous-error measures (e.g., RMSE), exceedance detection, and calibration diagnostics; uncertainty must propagate from sensors through reporting logic to decisions. Utilities balance latency and confidence, weigh false positives/negatives for status, and adopt automated recalibration, adaptive sampling, and provenance. Explainability using feature-importance and spatiotemporal sensitivity enables root-cause attribution and audit verification (Riyadh & Peleato, 2025).

Discussion

Discussion integrates results into a compliance scheme for real-time water quality. Although basin-scale assessments expose trade-offs in indicator choice (Sun et al., 2025), the scheme aligns taxonomies with monitoring via change logs, timestamped provenance, and automated checks at ingestion. Land-use hydrologic variability guides sensor placement and alerts (Shiferaw et al., 2025). Granularity and timeliness must be balanced against false alarms; design hinges on strict metadata, interoperable APIs, and immutable trails. Validation mitigates sensor gaps and semantic drift using cross-checks and thresholds, while stewards, versioned logic, and on-demand evidence and metrics on accuracy, efficiency, and auditability enable adaptive, ethical, scalable deployments.

Limitations

Although the model targets real-time compliance, cadence mismatches, missingness, calibration drift, and representativeness gaps undermine fidelity (Avila et al., 2025; Pejin et al., 2025). Sampling modality and detection limits bias exceedance inference, weakening compliance claims (Pejin et al., 2025). Evolving taxonomies risk semantic drift and brittle mappings; without human oversight, changes can cascade errors. Audit trails may be incomplete when logs or provenance/chain-of-custody are unverifiable. Latency, throughput, and storage burden on-demand reporting under legacy or low-budget IT. Transferability and adoption depend on governance/trust, data-sharing, and liability across jurisdictions. Priorities include sensitivity analyses, provenance sampling, staged pilots, and stakeholder-led acceptance testing.

Conclusion

This synthesis positions the framework as an operational bridge between compliance and real-time reporting. Although mandates and formats shift, taxonomy mapping and append-only audit trails preserve interoperability and change traceability; these yield compliance accuracy, faster reporting, auditability, adaptability, and satisfaction. For utilities, it advances institutional alignment, stewardship, and adaptive taxonomies without overhauls under interoperable standards. The approach aligns with urban resilience and reuse requiring on-demand verification (Piazza et al., 2025) and suits resource-constrained reuse needing quality (Duan et al., 2025). Limitations include technical burdens, institutional lags, and socio-legal constraints; priorities: pilots, cost-benefit, and acceptance. They strengthen public trust and resilience.

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