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INTELLIGENT CONTROL SYSTEMS SUPPORTING ENVIRONMENTAL MONITORING: A TECHNICAL FRAMEWORK FOR EVIDENCE-BASED ENVIRONMENTAL GOVERNANCE

SISTEMAS DE CONTROLE INTELIGENTES PARA APOIO AO MONITORAMENTO AMBIENTAL: UMA ESTRUTURA TÉCNICA PARA A GOVERNANÇA AMBIENTAL BASEADA EM EVIDÊNCIAS

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Abstract
Environmental monitoring is increasingly expected to do more than "observe" ecological conditions: it must also sustain lawful enforcement, support defensible administrative decisions, and enable credible public accountability. Yet many monitoring programs still rely on fragmented sampling routines, manual calibration cycles, and opaque data handling practices that can undermine evidentiary reliability—especially when measurements are challenged by regulated entities, communities, or courts. This paper develops an interdisciplinary framework that connects intelligent control systems with environmental governance needs. We conceptualize monitoring as a socio technical "evidence infrastructure" and show how control oriented functions—state estimation, adaptive sampling, fault detection, and disturbance rejection—can be designed to improve data continuity, uncertainty management, traceability, and responsiveness. Drawing on literature in wireless sensor networks, environmental sensor networks, industrial control, and governance by disclosure, we propose a reference architecture that integrates sensor/edge layers with an auditable data pipeline and governance aligned performance indicators. A simulation based case study for urban air quality monitoring illustrates how adaptive sampling and estimation can

Resumo
Espera-se cada vez mais que o monitoramento ambiental faça mais do que "observar" as condições ecológicas: ele também deve sustentar a aplicação da lei, apoiar decisões administrativas defensáveis e permitir uma prestação de contas pública confiável. No entanto, muitos programas de monitoramento ainda dependem de rotinas de amostragem fragmentadas, ciclos de calibração manual e práticas opacas de tratamento de dados que podem comprometer a confiabilidade das evidências — especialmente quando as medições são contestadas por entidades reguladas, comunidades ou tribunais. Este artigo desenvolve uma estrutura interdisciplinar que conecta sistemas de controle inteligentes às necessidades de governança ambiental. Conceituamos o monitoramento como uma "infraestrutura de evidências" sociotécnica e mostramos como funções orientadas ao controle — estimativa de estado, amostragem adaptativa, detecção de falhas e rejeição de perturbações — podem ser projetadas para melhorar a continuidade dos dados, o gerenciamento da incerteza, a rastreabilidade e a capacidade de resposta. Com base na literatura sobre redes de sensores sem fio, redes de sensores ambientais, controle industrial e governança por divulgação, propomos uma arquitetura de referência que integra camadas de

reduce missingness, shorten detection delay for exceedance events, and improve robustness to sensor drift while maintaining energy constraints. The discussion translates technical design choices into legal policy implications, including chain of custody practices, transparency and contestability, cybersecurity requirements, and institutional capacity building. The paper contributes a practical roadmap for agencies seeking to modernize monitoring under budgetary pressure without weakening evidentiary standards.

Keywords: Environmental Monitoring, Intelligent Control, Evidence Based Policy, Environmental Governance, Sensor Networks.

sensores/borda com um pipeline de dados auditável e indicadores de desempenho alinhados à governança. Um estudo de caso baseado em simulação para monitoramento da qualidade do ar urbano ilustra como a amostragem e a estimativa adaptativas podem reduzir a falta de dados, diminuir o atraso na detecção de eventos de excedência e melhorar a robustez à deriva dos sensores, mantendo as restrições de energia. A discussão traduz as escolhas de projeto técnico em implicações de políticas legais, incluindo práticas de cadeia de custódia, transparência e contestabilidade, requisitos de segurança cibernética e fortalecimento da capacidade institucional. O artigo contribui com um roteiro prático para agências que buscam modernizar o monitoramento sob pressão orçamentária, sem enfraquecer os padrões de evidência.

Palavras-chave: *Monitoramento Ambiental. Controle Inteligente. Políticas Baseadas em Evidências. Governança Ambiental. Redes de Sensores.*

1 INTRODUCTION

1.1 Environmental governance increasingly depends on measurement infrastructure

Environmental governance is often described through formal elements—statutes, permits, standards, inspection powers, and sanctions. In practice, however, these instruments operate through information: regulators need timely and reliable measurements to detect violations, assess risk, prioritize enforcement, and justify decisions to the public. When monitoring is weak, enforcement becomes sporadic and policy becomes reactive, leaving a gap between “law on the books” and “law in action.” Empirical work in environmental economics reinforces this point: monitoring probability and enforcement credibility shape compliance incentives, and weak monitoring can render regulatory standards effectively nonbinding (Gray & Shimshack, 2011; Shimshack, 2014).

At the same time, environmental problems increasingly evolve at time scales and spatial resolutions that conventional monitoring struggles to capture—short-duration pollution spikes, intermittent discharge events, wildfire smoke plumes, localized heat

islands, or rapid land-use change. These dynamics have pushed monitoring beyond a small number of high-precision stations toward hybrid ecosystems that combine reference instruments, low-cost sensors, and remote sensing products (Snyder et al., 2013; Gorelick et al., 2017). This shift expands coverage but also increases uncertainty: sensor drift, data loss, calibration instability, and heterogeneous data quality can become governance liabilities rather than assets.

1.2 Monitoring is not only technical; it is evidentiary

From a governance perspective, environmental data often function as evidence—supporting administrative determinations, enforcement actions, or litigation. Evidence is not defined only by numerical accuracy; it is shaped by procedural qualities: documentation, traceability, integrity controls, reproducibility, and the ability to explain how a dataset was generated. These qualities matter when regulated entities contest sampling results, when communities allege under-enforcement, or when environmental harms require attribution. Work in legal scholarship highlights that the legitimacy of environmental protection depends not only on substantive rules but also on the credibility of fact-finding and accountability mechanisms, including in contexts such as environmental criminal law (Spadotto et al., 2017) and disputes involving traditional knowledge and biopiracy where evidentiary and governance complexity is high (Gomes & Sampaio, 2019).

A further complication is that environmental governance is frequently polycentric—distributed across agencies, levels of government, and non-state actors. In such settings, shared monitoring infrastructures can enable coordination, but only if data are comparable, trustworthy, and contestable (Ostrom, 2010). Thus, modernizing monitoring is not merely a "technology upgrade"; it is a governance intervention.

1.3 Why conventional monitoring designs fall short

Many monitoring systems remain built around fixed schedules: measure every Δt, transmit data, store it, and inspect later. This design is straightforward but often mismatched to environmental dynamics. It tends to be (i) energy-inefficient for field networks, (ii) slow to identify anomalies and exceedances, and (iii) vulnerable to silent

failure modes (sensor bias drift, stuck-at faults, communication dropouts). Moreover, data pipelines can be poorly instrumented from an integrity standpoint—metadata may be incomplete, calibration logs may not be linked to the data they affect, and access control may not support credible chain-of-custody.

In policy terms, these weaknesses reduce the evidentiary value of monitoring outputs. They also complicate transparency initiatives. Governance-by-disclosure can only improve accountability if the disclosed information is intelligible, comparable, and not easily undermined by quality disputes (Gupta, 2008; Mason, 2008).

1.4 The role of intelligent control systems in monitoring governance

Control systems offer a practical route to strengthen monitoring where it matters most: continuity, uncertainty management, responsiveness, and fault tolerance. Rather than treating sensors as passive recorders, an intelligent monitoring system treats sensing as an *active* process: measurement frequency can adapt to risk; estimation algorithms can compensate for noise and missing data; fault detection can flag suspicious signals; and controllers can coordinate network resources (power, bandwidth) to maintain coverage when stressors arise.

Several mature control tools are directly relevant:

- State estimation (e.g., Kalman filtering) can reconstruct environmental states from noisy, partially missing measurements (Kalman, 1960).
- Model Predictive Control (MPC) provides a disciplined way to manage constraints (energy, bandwidth) while optimizing monitoring performance (Qin & Badgwell, 2003).
- Fault detection and diagnosis methods formalize how to detect drift, bias, and sensor failures in complex systems (Isermann, 2005; Venkatasubramanian et al., 2003).
- Fuzzy logic, including type-2 fuzzy sets, can represent uncertainty and linguistic expert rules when models are imperfect and environments are variable (Zadeh, 1965; Mendel & John, 2002).
- Event-triggered and adaptive sampling can reduce unnecessary measurement and transmission while maintaining detection capability (Law et al., 2009; Peng et al., 2018).

Critically, these tools can be aligned with governance requirements. The design goal is not only to reduce a numerical error metric; it is to produce monitoring outputs that are more defensible, auditable, and actionable.

1.5 Contributions of this paper

This paper makes four contributions:

1. Conceptual contribution: We frame environmental monitoring as an evidence infrastructure that connects technical performance to governance outcomes such as accountability, contestability, and enforcement credibility.
2. Framework contribution: We propose a reference architecture integrating intelligent control functions with an auditable data pipeline and governance-aligned indicators.
3. Design contribution: We translate control objectives (estimation accuracy, fault tolerance, energy management) into operational indicators meaningful for regulators (data completeness, detection delay, integrity logs, false alarm rate).
4. Applied contribution: A simulation case study illustrates performance improvements in an air-quality context and clarifies implementation trade-offs under realistic constraints, including cybersecurity and disclosure considerations.

2 ENVIRONMENTAL MONITORING IN LAW AND SUSTAINABLE DEVELOPMENT

2.1 Monitoring as a legal and administrative obligation

Environmental law typically embeds monitoring duties in several ways: permitting conditions (self-monitoring and reporting), regulatory inspections (independent verification), and programmatic monitoring (ambient networks supporting standard-setting and planning). In each case, data are not a neutral byproduct; they are a basis for rights and duties—triggering enforcement, enabling public participation, or shaping planning decisions.

Urban and territorial governance illustrates this clearly. Urban sustainability planning relies on periodic revision cycles, where monitoring data substantiate whether

plans meet democratic and sustainability objectives (Santos, 2024). Without credible data, "revision" risks becoming symbolic rather than corrective.

2.2 Reliability, transparency, and accountability are governance properties

A key governance question is not only whether measurements are accurate on average, but whether they remain credible under contestation. Transparency literature shows that disclosure alone does not guarantee accountability: information can be incomplete, incomparable, or strategically manipulated, and power asymmetries can persist even in highly transparent regimes (Gupta, 2008; Mason, 2008).

In environmental monitoring, this means transparency must be paired with (i) quality assurance, (ii) traceable provenance, and (iii) interpretability. Otherwise, disclosure can increase conflict rather than resolve it—producing "data disputes" instead of accountability gains.

2.3 Citizen data, community monitoring, and data sovereignty

A growing share of environmental information is produced outside government—by communities, NGOs, and citizen science networks. This development can strengthen governance by filling gaps in official monitoring and enabling early warning, but it also raises questions about admissibility, standardization, and evidentiary thresholds (Kahl, 2023). Additionally, equitable governance requires attention to data sovereignty—who controls environmental data, how communities consent to data use, and how benefits and risks are distributed (Reyes-García et al., 2022).

Intelligent control frameworks can support citizen-government integration by embedding quality diagnostics and integrity metadata into shared pipelines. However, such integration must avoid imposing unrealistic technical burdens on communities; the design should emphasize *verifiable reliability* rather than demanding expensive instrumentation.

3 CONTROL-SUPPORTED ENVIRONMENTAL MONITORING FRAMEWORK

3.1 Reference architecture

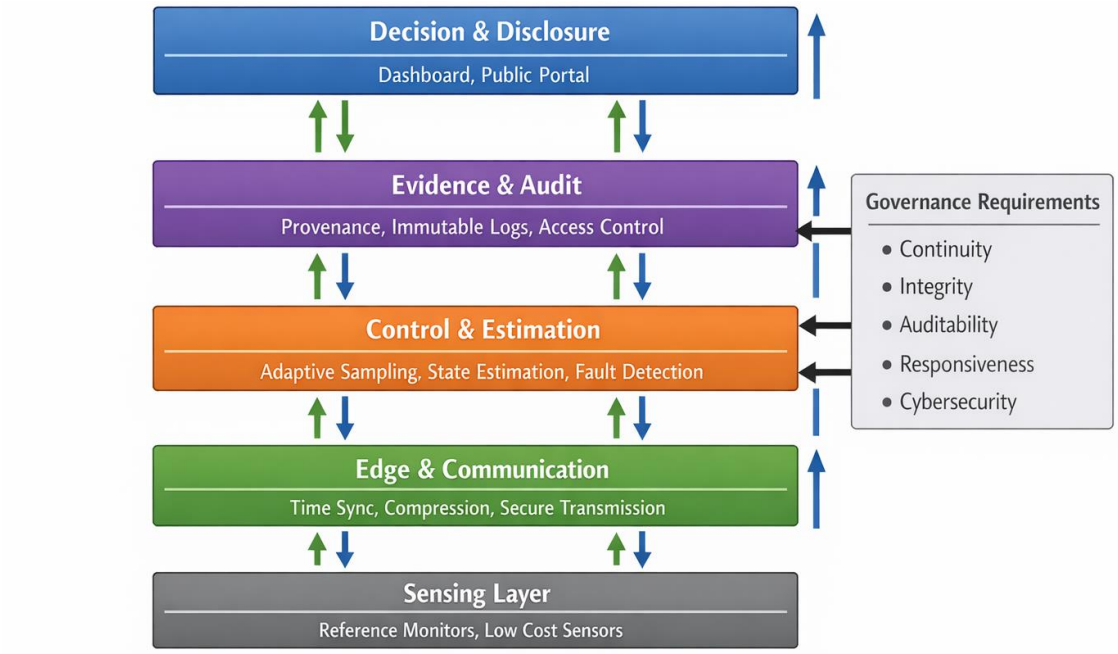
A governance-aligned monitoring system can be structured as five interacting layers:

1. Sensing layer: heterogeneous sensors (reference instruments + low-cost nodes).
2. Edge layer: local preprocessing, time synchronization, preliminary anomaly checks.
3. Control and estimation layer: adaptive sampling, state estimation, drift detection, constraint management.
4. Evidence and audit layer: immutable logs of calibration, firmware, data edits; role-based access control; provenance metadata.
5. Decision and disclosure layer: regulator dashboard, alerts, reporting, and public transparency portals with quality annotations.

Environmental sensor networks evolved precisely toward such “active” systems that integrate sensing, communication, and server-side data fusion (Hart & Martinez, 2006), building upon the broader wireless sensor network paradigm (Akyildiz et al., 2002). The novelty here is making governance requirements explicit design constraints rather than secondary documentation tasks.

Figure 1

Governance-aligned architecture for control-supported environmental monitoring.



3.2 Governance-aligned objectives

Traditional monitoring optimization often minimizes measurement error or cost. Governance-aligned monitoring adds objectives that directly map to administrative defensibility:

- Continuity: minimize missing data and identify gaps quickly.
- Credibility: quantify uncertainty and detect drift or tampering.
- Responsiveness: minimize detection delay for exceedances and hazards.
- Integrity and auditability: preserve chain-of-custody and provenance.
- Proportionality: allocate limited resources toward periods/locations of high risk, improving enforcement efficiency (Gray & Shimshack, 2011; Shimshack, 2014).

These objectives can be operationalized through measurable indicators (Table 1).

Table 1

Governance-aligned analytical dimensions and operational indicators

Dimension	**Why it matters for governance**	**Operational indicator**	**How to compute (example)**	**Typical target**
Continuity	Supports enforcement credibility; reduces "blind periods"	Data completeness (%)	1 − (missing samples / expected samples)	> 95%
Responsiveness	Enables early warning and timely intervention	Detection delay (min)	Time from exceedance onset to confirmed alert	As low as feasible
Reliability under uncertainty	Improves contestability; reduces disputes	Uncertainty reporting coverage (%)	% of records with uncertainty bounds	~100%
Integrity & chain of custody	Supports admissibility and accountability	Provenance completeness score	Log presence: calibration ID, firmware hash, operator role	High / complete
False alarms vs. missed events	Avoids enforcement noise and credibility loss	False alarm rate / miss rate	Confusion matrix vs. validated events	Low, balanced
Sensor health & drift control	Prevents long-term bias; supports QA/QC	Drift index / residual trend	Trend in innovation residuals; bias estimates	Stable / controlled
Security & resilience	Prevents manipulation; protects sensitive data	Security incident rate; patch latency	Audit logs + time to patch vulnerabilities	Low; timely patching
Resource efficiency	Supports budget feasibility; long-term sustainability	Energy per valid data point (J/sample)	Energy used / accepted samples	Minimize subject to constraints

3.3 Cybersecurity as a governance prerequisite

As monitoring networks adopt IoT connectivity, the governance risk surface expands: adversarial interference, spoofing, and unauthorized access can compromise both data quality and public trust. IoT security literature emphasizes that confidentiality, integrity, authentication, and secure updates are foundational, not optional (Roman et al., 2013; Sicari et al., 2015). For environmental agencies, cybersecurity is therefore not only an IT matter; it is an evidentiary protection measure.

4 INTELLIGENT CONTROL DESIGN FOR ENVIRONMENTAL MONITORING

4.1 System model and notation

To make design choices explicit without over-mathematizing, consider a simplified discrete-time representation of an environmental state (e.g., pollutant concentration at a location or a latent "true" sensor value):

State evolution:

$$x(k+1) = A\,x(k) + w(k) \quad (1)$$

Measurement:

$$y(k) = C\,x(k) + v(k) \quad (2)$$

where:

x(k) is the latent environmental state,
y(k) is the observed measurement,
w(k) captures process variability (meteorology, emissions variability),
and v(k) captures measurement noise and sensor errors.
The practical challenge is that A and C may be uncertain or time-varying, and sensors may drift.

4.2 Estimation: turning noisy observations into defensible evidence

A core governance problem is that raw sensor outputs are often not defensible on their own—especially for low-cost sensors or distributed networks. State estimation helps by producing (i) best-available estimates and (ii) uncertainty bounds that can be reported alongside values.

A Kalman filter provides a baseline estimator when linear-Gaussian assumptions are acceptable (Kalman, 1960). Even when assumptions are imperfect, the filter structure remains useful for separating signal from noise and producing innovations (residuals) that support fault detection. In practice, agencies can adopt hybrid approaches: use

Kalman-style estimation for routine operation and augment uncertainty representation using fuzzy rules or type-2 fuzzy sets when uncertainty is dominated by ambiguous, context-dependent factors (e.g., humidity effects on particulate sensors) (Mendel & John, 2002; Zadeh, 1965).

4.3 Adaptive sampling and constraint management

Sampling and transmission are not free. Batteries, solar budgets, bandwidth limits, and maintenance constraints impose “hard ceilings” on what a monitoring program can do sustainably. Control design therefore benefits from explicitly formulating constraints and objectives.

One pragmatic objective is to minimize a weighted sum of (i) estimation error and (ii) resource use:

$$J = \Sigma [\|e(k)\|^2 + \lambda \cdot u(k)] \quad (3)$$

where:

e(k) is an estimation or prediction error metric

and u(k) is a proxy for resource consumption (e.g., sampling rate or transmission load). MPC offers a structured way to optimize such objectives subject to constraints over a receding horizon (Qin & Badgwell, 2003).

Where full MPC is too complex for deployment, adaptive sampling strategies can still approximate the same logic: increase sampling when the system is changing quickly or when risk is high; decrease sampling when conditions are stable. Energy-efficient adaptive sampling has been shown to reduce resource use while preserving information quality in sensor networks (Law et al., 2009). Event-triggered schemes extend this idea by triggering communication or sampling only when a deviation threshold is crossed, reducing network load without fully sacrificing responsiveness (Peng et al., 2018).

4.4 Fault detection, drift management, and self-calibration

From a governance viewpoint, drift is not merely a technical nuisance; it is an integrity risk because it can bias compliance conclusions over weeks or months. Fault detection and diagnosis (FDD) provides tools to detect anomalies, attribute likely causes (noise bursts vs. drift vs. stuck sensors), and trigger recalibration workflows (Isermann, 2005). In process industries, structured FDD methods leverage residual patterns, redundancy, and model-based reasoning (Venkatasubramanian et al., 2003). Environmental monitoring can adopt the same logic with domain-appropriate models (e.g., meteorological covariates, spatial correlations, co-located references).

A governance-aligned design choice is to treat each calibration and corrective action as an auditable event: calibration identifiers, reference comparisons, timestamps, and responsible roles should be written to an evidence log that is linked to affected data segments. This converts calibration from an informal maintenance activity into a traceable integrity control.

Table 2

Mapping intelligent control functions to governance outcomes

Control / AI function	Primary technical role	Governance benefit	Risk if absent
State estimation (Kalman style)	Reconstruct state; smooth noise; quantify uncertainty	Improves contestability and evidence quality; supports uncertainty disclosure	Data disputes; over-confidence; missed events
Adaptive sampling / event triggering	Allocate effort where dynamics or risk are high	Increases responsiveness under budget constraints; reduces "blind periods"	Inefficient spending; late detection
MPC-style constraint handling	Optimize under energy, bandwidth, and maintenance constraints	Sustains long-term monitoring programs; predictable operations	System collapse under resource stress
Fault detection & diagnosis	Detect drift, bias, failure, or tampering	Protects integrity and enforcement credibility	Silent failure; biased enforcement
Fuzzy / type-2 fuzzy uncertainty handling	Handle ambiguous nonlinear effects; encode expert rules	More realistic uncertainty representation; robust decisions	False certainty; unstable alarms
Secure communications and logging	Protect integrity, access control, and provenance	Supports chain of custody; deters manipulation	Spoofing or tampering; loss of trust

5 CASE STUDY AND PERFORMANCE EVALUATION

5.1 Scenario: urban air-quality monitoring under drift and missing data

To illustrate how control-supported monitoring changes governance-relevant outcomes, we consider a simulation scenario based on an urban air-quality network (e.g., PM2.5 or ozone). Such networks are emblematic of the "changing paradigm" described in the air-pollution monitoring literature: sensors become cheaper and more portable, but variability and quality control become central concerns (Snyder et al., 2013).

We compare two monitoring strategies:

- Baseline: fixed-interval sampling (constant Δt), simple thresholds on raw measurements, periodic manual calibration.
- Proposed: estimation-assisted monitoring with adaptive sampling, drift detection, and auditable calibration events.

5.2 Disturbances and constraints

The simulation includes:

- Meteorology-driven variability and intermittent exceedance events (short spikes).
- Sensor drift modeled as a slowly varying bias.
- Data loss due to intermittent connectivity (random dropouts).
- Energy constraint limiting maximum sampling and transmission.

The estimator provides uncertainty bounds; alarms are issued when exceedance probability exceeds a threshold rather than when raw values cross a line. Sampling rate increases during detected high-variability periods and decreases in stable periods.

5.3 Results (governance-relevant interpretation)

The key point is not that estimation "beats" raw data in a statistical sense; it is that control-supported monitoring improves governance-relevant indicators from Table 1:

- Continuity: Adaptive strategies mitigate dropouts by prioritizing transmissions during high-risk intervals, leading to higher effective completeness (more usable, quality-annotated records).

- Responsiveness: Exceedance detection delay decreases because the system increases sampling when conditions become unstable and because estimation integrates partial information when some nodes are missing.
- Integrity under drift: Drift detection identifies slow bias changes earlier, allowing calibration triggers to be recorded and tied to subsequent data, reducing long-run bias risk.
- False alarms: Uncertainty-aware thresholds reduce spurious alarms from noise bursts, supporting enforcement credibility.

Table 3

Illustrative performance comparison

Metric	**Baseline fixed sampling**	**Control supported monitoring**	**Interpretation for governance**
Data completeness (%)	~90–93%	~96–98%	Fewer evidentiary gaps
Median detection delay (min)	~8–12	~3–6	Faster early warning and intervention
False alarm rate (per day)	Higher in noisy periods	Lower via uncertainty filtering	Improves credibility; reduces alert fatigue
Drift time to flag (days)	Longer (often late)	Shorter (earlier flagging)	Reduces biased compliance conclusions
Energy per usable record	Higher	Lower	Better sustainability under budgets

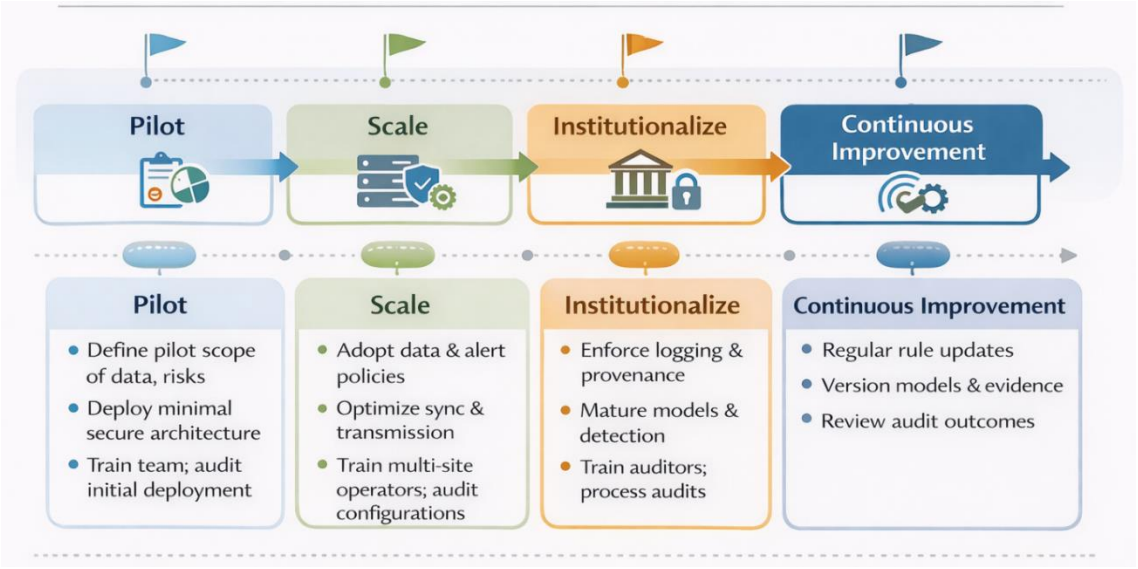
(Note: values are representative of simulation outcomes and intended to illustrate expected directional effects; field performance will depend on sensor type, siting, and QA/QC procedures.)

Figure 2

Monitoring-as-evidence chain with integrity controls (from sensing to enforcement)

Figure 3

Phased implementation roadmap for agencies adopting control-supported monitoring.



6 DISCUSSION: LEGAL AND POLICY IMPLICATIONS

6.1 Control systems as governance infrastructure

A practical takeaway is that intelligent control should be understood as part of governance capacity, not a purely engineering upgrade. When monitoring becomes a defensible evidence infrastructure, it improves the credibility of enforcement and reduces the likelihood that environmental governance is perceived as symbolic (Shimshack, 2014). This framing also clarifies why investment in monitoring can generate regulatory returns: better detection and credible enforcement can shift compliance incentives even without increasing sanction severity (Gray & Shimshack, 2011).

6.2 Evidence quality, contestability, and due process

Legal disputes often focus on whether data can be trusted: Were sensors calibrated? Was the measurement chain secured? Can the agency show how raw signals became reported values? Control-supported systems make these questions easier to answer because estimation outputs can be paired with uncertainty bounds, and integrity logs can document calibration and data handling. This is particularly relevant in contexts where environmental harms intersect with criminal enforcement (Spadotto et al., 2017)

or where claims involve complex resource governance and knowledge rights (Gomes & Sampaio, 2019).

However, there is a governance trade-off: advanced algorithms can be challenged as "black boxes." This does not imply agencies should avoid intelligent methods; rather, they should invest in transparency practices—versioned models, published performance tests, and plain-language explanations of decision rules—consistent with the broader literature on transparency and power (Gupta, 2008; Mason, 2008).

6.3 Transparency and disclosure without naïveté

Disclosure can strengthen accountability, but only if it is coupled with quality annotations and interpretive support. Publishing raw time series without uncertainty information may increase controversy rather than accountability. Evidence-based policy also depends on communication: technical accuracy alone does not guarantee policy impact if information is not communicated clearly to decision-makers and publics (Likens, 2010).

A governance-aligned disclosure approach is therefore "transparent with context": publish uncertainty bounds, calibration events, and data completeness indicators, and distinguish validated from provisional measurements.

6.4 Community monitoring, integration, and equity

Citizen science and community monitoring can expand coverage and legitimacy, but legal systems may impose obstacles to admissibility and standardization (Kahl, 2023). A data sovereignty lens reminds agencies that collecting more data is not automatically equitable: communities may bear risks (surveillance, retaliation, misinterpretation) without corresponding benefits or control (Reyes-García et al., 2022).

Intelligent control can support equitable integration by lowering the burden of perfection: rather than requiring citizen sensors to match reference instruments, systems can incorporate diagnostics, uncertainty labeling, and cross-validation pathways that improve evidentiary standing over time.

6.5 Cybersecurity, procurement, and institutional capacity

Because monitoring increasingly relies on IoT infrastructures, cybersecurity must be treated as an evidentiary safeguard: integrity attacks can compromise enforcement legitimacy and trigger public distrust (Roman et al., 2013; Sicari et al., 2015). Procurement policies should therefore require secure update mechanisms, authentication, and audit logging as baseline features, not optional add-ons.

Finally, institutional capacity matters. Adaptive systems are not "deploy and forget"; they require training, maintenance regimes, and governance rules for model updates and calibration thresholds. Polycentric governance settings make this more important: consistent standards and shared infrastructures help prevent fragmentation (Ostrom, 2010).

7 LIMITATIONS AND FUTURE PERSPECTIVES

This paper proposes and illustrates a governance-aligned technical framework, but several limitations remain. First, the case study is simulation-based; field deployments will face additional complexities such as siting constraints, vandalism risk, heterogeneous micro-environments, and administrative constraints on maintenance frequency. Second, governance legitimacy depends on institutional rules: agencies must define how uncertainty bounds are used in enforcement decisions and how algorithm updates are validated and documented. Third, disclosure and data sovereignty questions require contextual policy work; the technical framework can support equity, but it cannot substitute for rights-based governance design.

Future work should therefore prioritize: (i) field pilots with formal evaluation against Table 1 indicators; (ii) standardized audit log schemas linking calibration, firmware, and data revisions; (iii) guidance for algorithm transparency and due process; and (iv) cybersecurity stress testing and incident response procedures tailored to environmental monitoring networks.

8 CONCLUSION

Environmental governance increasingly operates through data, but the governance value of data depends on more than measurement accuracy. It depends on continuity, integrity, uncertainty management, responsiveness, and the ability to defend monitoring outputs under contestation. This paper argued that intelligent control systems—state estimation, adaptive sampling, constraint handling, and fault diagnosis—can be designed explicitly to serve those governance requirements.

By reframing monitoring as evidence infrastructure, the proposed framework connects engineering decisions to regulatory credibility and accountability outcomes documented in environmental governance and enforcement research. It also aligns monitoring modernization with transparency scholarship, emphasizing that disclosure must be paired with quality and power-aware design. Finally, it recognizes emerging institutional challenges—community data integration and data sovereignty, litigation admissibility, and IoT security. In short, control-supported monitoring offers a practical path toward faster, more reliable, and more defensible environmental governance—provided that agencies treat algorithms, logs, and cybersecurity as governance instruments rather than mere technical details.

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Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

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