Ethical Use of Scientific Evidence in Watershed Governance: An Integrative Review of Policy, Participation, and Accountability in Indonesia

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ABSTRACT

Water policies require reliable scientific information, but translating environmental measurements into regulatory decisions also raises questions of responsibility, participation and fairness. These questions are especially important in tropical watersheds, where seasonal variability and different natural or human-derived inputs complicate interpretation. This critical integrative review examines how environmental evidence can inform accountable watershed governance, with particular attention to Indonesian policy and documented river-basin cases. Relevant publications were identified through targeted discovery in the Directory of Open Access Journals (DOAJ), searches of publisher and journal archives, backward reference checking, and consultation of the Indonesian legal database (JDIH BPK). The principal literature window covered 2019–October 2026, while older foundational works were retained for their conceptual or scientific significance. Sources were purposively selected for policy relevance, identifiable provenance, and explicit treatment of evidence, institutions or environmental justice; no exhaustive or statistically representative search is claimed. Indonesian studies of the Batang Arau, Brantas, Krueng Aceh, Citarum and Poso watersheds show practical tensions involving inter-agency coordination, public participation, information access and stakeholder roles. Cross-disciplinary synthesis also identifies four interpretive challenges: distinguishing observation from causal attribution, matching monitoring to management timescales, respecting the boundary between scientific inference and statutory compliance, and evaluating unequal consequences of decisions. In response, we propose a six-stage evidence-to-decision accountability pathway spanning joint problem definition, contextual diagnosis, uncertainty qualification, ethical appraisal, deliberation and adaptive review. Geological and water-quality information is treated as decision support, not as an automatic determination of environmental harm or legal liability. The framework is a conceptual proposal requiring testing through policy records, monitoring programmes and stakeholder engagement before effectiveness can be established.

Keywords: watershed governance, environmental ethics, evidence-informed policy, public participation, Indonesia

INTRODUCTION

Watershed management is a public decision-making problem as well as an environmental one. Rivers link communities and administrative territories through water, sediments and dissolved substances, but responsibilities for monitoring, land use, pollution control and resource allocation are distributed among institutions. Consequently, technical evidence cannot be separated from decisions about whose concerns are recognized, which risks justify intervention and who bears the cost of inaction. Research on river-basin planning and adaptive governance cautions that administrative boundaries and standardized indicators may overlook cross-scale processes and social consequences (Molle, 2009; Pahl-Wostl et al., 2012; Moore et al., 2024).

Geological evidence is relevant because the mineral composition and weathering behavior of rocks influence baseline concentrations and ionic ratios. Gibbs (1970) established the importance of rock dominance and other

broad controls on natural water chemistry; Gaillardet et al. (1999) subsequently demonstrated the value and limitations of major-ion budgets for estimating silicate weathering. In tropical settings, regional lithology interacts with runoff and sediment export to shape the transport of dissolved inorganic carbon (DIC). An analysis of mountainous rivers in India's Western Ghats reported considerable differences among geological terrains and linked DIC export to climate and runoff conditions (Reddy et al., 2019). These findings make geology relevant to policy interpretation, although they do not imply that all measured dissolved carbon is derived from rock weathering.

The hydrological context is equally important. A watershed's chemical signature can shift when shallow groundwater, wetlands, or deeper aquifers contribute different proportions of streamflow. In northern Australia's wet–dry tropics, Duvert et al. (2020) documented a seasonal change between predominantly biogenic and geogenic sources of riverine DIC. Recent syntheses emphasize that land–river connectivity shapes water-quality responses under changing climatic conditions (Li et al., 2024). A single concentration measured at one station therefore cannot consistently identify a source, describe a long-term trend, or establish the effect of a human activity without adequate spatial and temporal context.

Yet the relationship between scientific diagnosis and administrative decisions is not straightforward. Water policy requires actionable thresholds, coherent responsibilities and predictable procedures, while hydrogeochemical interpretations often depend on uncertain mixing, incomplete monitoring and competing explanations. Kotamäki et al. (2024) discuss this broader tension between scientific evidence, law and uncertainty. Meanwhile, research on science–policy relations shows that credible knowledge must also be relevant and legitimate to the people expected to use it (Cash et al., 2003). More data alone do not guarantee better decisions if the assumptions used to convert observations into regulatory judgments remain opaque. Environmental justice theory further requires attention to the distribution of burdens, recognition of affected groups, and their meaningful participation in decisions (Schlosberg, 2004, 2013).

Indonesia provides a relevant setting for examining these connections. Government Regulation No. 37 of 2012 addresses integrated watershed management, Law No. 17 of 2019 governs water resources, and Government Regulation No. 22 of 2021 provides rules for environmental protection and water quality. The policy literature has identified institutional and participatory challenges: Pambudi (2019) reviewed fragmentation among watershed agencies; Sulistyaningsih et al. (2021) examined policy arrangements in the Brantas basin; and Renaldi and Frinaldi (2022) documented limits to transparency and coordination in the Batang Arau watershed. More recent work links river governance to formal–informal institutional relations, collaborative action and justice concerns (Binada, 2023; Abdillah et al., 2024; Putri et al., 2024). These studies do not establish that source attribution is routinely misused by particular agencies. Rather, they supply documented contexts in which the use and communication of environmental evidence warrant critical evaluation. This review asks how scientific evidence, uncertainty and affected publics should be connected to accountable watershed decisions. Its contribution is an interpretive policy framework, not a new geochemical model or an evaluation of a particular government programme.

METHODOLOGY

Review design and source selection

This article employed a critical integrative literature review with interpretive policy analysis, rather than a systematic review or meta-analysis. The purpose was to compare different forms of knowledge—environmental monitoring, water governance research, environmental ethics and Indonesian law—to develop an explicit conceptual explanation of how evidence enters public decisions (Torraco, 2005; Snyder, 2019). The unit of synthesis was the source-supported proposition, not the number of papers mentioning a theme. This approach does not permit prevalence estimates or causal claims about the performance of Indonesian agencies.

Source discovery took place in October 2026. The indexed discovery component used the Directory of Open Access Journals (DOAJ) to locate relevant publications on watershed governance and community participation in Indonesia. Complementary targeted title and keyword searches were conducted across accessible publisher and journal archives, including journals in environmental policy, public administration and water science; cited

reference lists were checked for foundational works. The Indonesian legal corpus was retrieved from the official JDIH BPK regulation database. Search expressions combined terms such as ('watershed' OR 'river basin') AND ('governance' OR 'policy' OR 'participation' OR 'environmental justice') AND 'Indonesia'; supplementary searches combined 'water quality', 'scientific evidence', 'uncertainty', 'catchment', 'hydrology' and 'source attribution'. The principal publication window was January 2019 to 13 October 2026. Pre-2019 publications were retained only when they supplied a foundational concept, analytical method or continuing legal context. This procedure supports interpretive synthesis, not a claim of exhaustive database coverage or preregistration.

Screening followed an explicit qualitative sequence: (1) identify potentially relevant records or legal instruments; (2) check authorship, publication date, document type, DOI or official document identity, and remove duplicate citations; (3) examine titles and abstracts, followed by relevant full text or source sections when accessible; (4) exclude items outside watershed or water governance, studies that did not inform the review questions, unverifiable promotional sources, and legal summaries without an authoritative source; and (5) extract claims into thematic groups. Included sources had to make a traceable contribution to at least one strand—governance and institutions, scientific evidence and its limitations, justice and public participation, or applicable Indonesian policy. Conceptual and empirical papers were distinguished during extraction; non-Indonesian studies served as transferable conceptual or physical-process evidence, not proof of Indonesian governance outcomes. Because the original discovery process did not retain a complete hit-by-hit retrieval log, numerical identification, exclusion and inclusion totals cannot be reconstructed reliably. This is documented as a limitation, and the article does not present a PRISMA diagram or imply exhaustive coverage.

Analytical procedure and limits of inference

The analytical extraction matrix used five fields for each substantive claim: study or legal provenance; empirical observation or normative proposition; decision-making relevance; uncertainty or alternative interpretation; and implications for accountability. Sources were compared under five review questions: what evidence establishes; how spatial and seasonal variation limits inference; where evidence interacts with institutional authority; how unequal participation and impacts matter; and which safeguards permit decisions to be revised. Comparative coding identified four cross-cutting interpretive problems and informed the proposed six-stage pathway. The framework draws on distributive, procedural and recognitional environmental justice (Schlosberg, 2004, 2013), while treating transparency, proportionality and participation as normative evaluation criteria rather than measured causal effects. Indonesian examples were used as secondary case evidence, not as newly collected field data.

Legal interpretation was limited to the stated purpose, scope and amendment status of official instruments. The JDIH BPK record for Law No. 32 of 2024 confirms that the law primarily amends Law No. 5 of 1990 on conservation of living natural resources and ecosystems, and specifically repeals Articles 33 and 69(c) of Law No. 17 of 2019 on Water Resources. Law No. 17 of 2019 as a whole remains in force, subject to applicable amendments. This clarification is not a substitute for article-by-article legal analysis. No local regulatory inspection, stakeholder interviews, monitoring dataset or validation of governance effects was undertaken. Accordingly, the review separates evidence reported in cited Indonesian studies from the ethical and operational recommendations advanced here.

RESULTS

Hydrogeochemical evidence has explanatory value, but source attribution is conditional

The studies distinguish observations from explanations. Dissolved Ca, Mg, Na, bicarbonate and silica may reflect reactions between water and rock, but their levels can also be influenced by groundwater mixing, land use and other pathways. Gibbs (1970) identified broad controls on natural water chemistry, and Gaillardet et al. (1999) showed why atmospheric and non-silicate contributions must be assessed when interpreting weathering-related solute loads. These findings matter for water policy because a laboratory value without sampling context cannot by itself identify a responsible source or justify sanctions.

The distinction is acute for DIC. Huang et al. (2012) showed that tropical rivers transport inorganic and organic carbon in several fractions, but the total DIC flux is not the same as the CO2 consumed by silicate weathering or carbon demonstrably derived from bedrock. Soil respiration, aquatic metabolism, carbonate minerals, groundwater inputs, and anthropogenic influences can contribute to measured inorganic carbon. The seasonal source switch documented by Duvert et al. (2020) illustrates the magnitude of this attribution challenge. A regulator may therefore use DIC and alkalinity to understand a catchment's functioning, but it would be inappropriate to treat either parameter alone as conclusive evidence of contamination or of a climate-mitigation benefit.

A second distinction concerns natural background conditions and environmental harm. Different rock assemblages can produce different ionic compositions even in the absence of a particular land-use disturbance. Conversely, an anthropogenic signal can be obscured by high seasonal dilution or by the natural variability of a geogenic constituent. The policy problem is not to excuse pollution by invoking geology, but to avoid attributing changes to particular activities before a defensible comparison with relevant background conditions and other sources is available. Paired upstream–downstream measurements, rainfall history, discharge, and land-use evidence can improve interpretation, but their diagnostic power depends on the sampling design and the availability of appropriate comparison sites.

Table 1. Interpreting hydrogeochemical evidence for watershed decisions without exceeding its evidential limits

Evidence or indicator	Supported interpretation	Main competing explanation / limit	Responsible policy use
Lithology and mineralogy	Identify potentially reactive minerals and expected solute end-members	Weathering intensity, groundwater pathways and minor minerals vary spatially	Stratify catchments and select comparison stations
Major ions and ionic ratios	Indicate hydrochemical facies and candidate weathering/mixing processes	Agricultural inputs, evaporation, ion exchange and atmospheric deposition may overlap	Test alternative source explanations, not single-point blame
Alkalinity, bicarbonate and DIC	Describe carbonate-system conditions and inorganic carbon transport	Biogenic, geogenic and anthropogenic components can mix	Contextualize carbon cycling; do not equate with pollution compliance
Discharge and precipitation	Explain dilution, mobilization and time-varying loads	Event timing and antecedent moisture may dominate snapshots	Match monitoring intervals to hydrological decisions
Nitrate, sulfate and land use	Support investigation of human pressures when combined with context	Natural geological and atmospheric inputs may contribute	Trigger targeted follow-up and protective action where warranted
Groundwater–river connectivity	Clarify hidden sources and lagged impacts	Water age and mixing may be poorly constrained	Protect recharge zones and interpret delayed responses

Temporal and spatial mismatch can distort regulatory interpretation

River governance frequently requires information over seasons, years and management units, while the observed data may consist of small numbers of samples collected at convenient stations. Monitoring that documents a condition without testing the link between pressure, stressor and environmental state may not deliver the information necessary for adaptive management (Stoffels et al., 2024). Research on hydrological uncertainty similarly indicates that the recency of information and spatial coverage affect the reliability of predictions (Auer et al., 2024). In a tropical sub-watershed, measurements collected only under baseflow conditions could miss high-flow transfers from agricultural land; samples taken only during storms could underrepresent contributions from deeper groundwater.

The scale of inference must also match the scale of action. Chemical data from one river reach cannot automatically characterize every upstream tributary or be treated as representative of the entire basin. Moore et al. (2024) argue that water governance requires flexibility beyond a fixed boundary because hydrological effects, institutions and consequences interact across scales. Hydrological connectivity also creates time lags: current concentrations may reflect past disturbances, whereas current management interventions may not yield immediate chemical responses. Policies that demand a short, monotonic trend from inherently variable data risk both premature success claims and unjustified failures of compliance.

The strongest insight from these studies is methodological rather than numerical: fit-for-purpose sampling should begin with a decision question. If the objective is to identify a possible agricultural pressure, wet-season targeted sampling and comparison across land-use gradients may be necessary. If the objective is to distinguish weathering sources, geology, hydrogeochemical ratios and groundwater context become more important. If the objective is to evaluate a policy measure, repeated measurements before and after implementation must be complemented by hydrological normalization or suitable control locations. The same dataset may be informative for one objective and inadequate for another.

Indonesian policy instruments provide decision settings, not automatic evidence rules

Indonesian watershed governance is framed by several instruments with different functions. Law No. 32 of 2009 concerns environmental protection and management; Government Regulation No. 37 of 2012 addresses watershed management; Law No. 17 of 2019 governs water resources; and Government Regulation No. 22 of 2021 implements environmental protection and quality-management mechanisms (Republic of Indonesia, 2009, 2012, 2019, 2021). Their status must be read together with later legislation. Law No. 6 of 2023 amended provisions relevant to environmental and water resources regulation. Law No. 32 of 2024, whose principal subject is biological conservation, additionally repealed precisely Article 33 and Article 69 letter c of Law No. 17 of 2019; it did not repeal the entire 2019 water-resources law (Republic of Indonesia, 2023, 2024). This statement follows the official JDIH BPK status records and does not purport to resolve the legal effects of all related provisions.

A useful analytical distinction follows. Statutory standards and designated environmental objectives define compliance obligations, whereas lithology, ionic balance, source modeling, and DIC provide contextual evidence to interpret why a condition occurred, what risks might persist, and which corrective action is proportionate. In particular, interpreting a naturally elevated constituent must not be used to nullify an applicable legal standard, and identifying an anthropogenic contribution does not, by itself, establish legal liability. Environmental permitting and enforcement require evidence appropriate to the relevant rule, procedural safeguards and the competent authority's determination. The review therefore treats scientific diagnosis as an input to, rather than a replacement for, lawful decision-making. Table 2 sets out this proposed alignment with the main Indonesian instruments considered here.

The policy opportunity is to make the relation between evidence and authority explicit. At the planning stage, geological mapping can inform the placement of monitoring and groundwater protection. During water-quality assessment, source evaluation can help decide whether further sampling is needed and which pressures deserve attention. In intervention design, seasonal loads and land-use patterns can guide feasible actions. Finally, public reporting can separate measured concentrations, modeled contributions, formal compliance judgments and residual uncertainty. This separation is not currently demonstrated as a uniform administrative practice; it is proposed here as a defensible implementation principle.

Table 2. Indonesian policy settings and possible roles for catchment evidence (conceptual alignment, not a legal compliance checklist)

Instrument	Broad regulatory function	Evidence contribution proposed here
Law No. 32/2009 (as amended)	Environmental protection and management, public rights and responsibilities	Transparent environmental diagnosis, communication and participation

Government Regulation No. 37/2012	Management of watersheds as functional landscape units	Catchment delineation, geological stratification and coordinated monitoring
Law No. 17/2019 (amended; Arts. 33 and 69(c) repealed by Law No. 32/2024)	Water resources governance and management responsibilities	Groundwater–surface water linkages, source protection and seasonal availability
Government Regulation No. 22/2021	Environmental approvals, protection and water-quality management	Fit-for-purpose quality evidence, quality assurance and justified follow-up

Documented Indonesian governance cases and evidence translation

Indonesian empirical and policy studies provide concrete examples of problems at the science–administration boundary. Pambudi (2019) identifies cross-sectoral and territorial fragmentation in watershed management. In Batang Arau, Renaldi and Frinaldi (2022) describe limited disclosure of industrial waste information, bureaucratic delays and incomplete coordination. Sulistyaningsih et al. (2021) find uneven institutional responsibilities in Brantas policy arrangements, while Binada (2023) describes the contested but complementary roles of state and civic organizations. These results concern governance practice; none by itself establishes a specific geochemical source of contamination.

Research on Krueng Aceh links biophysical change to stakeholder and policy implementation analysis (Mulyawan et al., 2022). Citarum work discusses coordination and the inclusion of marginalized groups in environmental decisions (Abdillah et al., 2024; Putri et al., 2024). Evidence from Poso emphasizes the importance of organizational participation and knowledge of formal rules for collective watershed stewardship (Massiri et al., 2025). Table 3 maps these documented findings to the accountability functions proposed in this review. This is a comparison of published studies, not a cross-site evaluation using standardized primary data.

Table 3. Published Indonesian watershed evidence and its relevance to the proposed governance framework

Watershed / study	Source-supported finding	Accountability implication (proposed)
National perspective — Pambudi (2019)	Intersectoral and territorial integration remains a challenge	Identify responsible agencies and decision mandates
Brantas — Sulistyaningsih et al. (2021); Binada (2023)	Formal coordination and civic organizational roles are uneven and contested	Record formal/informal actors and the basis for participation
Batang Arau — Renaldi & Frinaldi (2022)	Information disclosure and cross-sector coordination gaps	Disclose evidence, assumptions and reasons for decisions
Krueng Aceh — Mulyawan et al. (2022)	Biophysical changes and policy implementation gaps were documented	Match monitoring evidence with policy duties
Citarum — Abdillah et al. (2024); Putri et al. (2024)	Collaboration and distributive/participatory justice are policy concerns	Test representation and distribution of consequences
Poso — Massiri et al. (2025)	Weak formal-rule knowledge and organizational involvement hinder collective action	Explain rights and support meaningful local engagement

The ethical risk lies in how evidence is used and whose interests it protects

Four ethical questions arise at the boundary between environmental evidence and governance. Epistemic responsibility asks whether measurement, interpretation and uncertainty have been reported separately. Distributive justice asks who carries the costs of an intervention, restriction or failure to act (Agyeman et al., 2002). Procedural and recognitional justice ask whose knowledge, rights and concerns are considered in problem formulation and decisions (Schlosberg, 2004, 2013). Intergenerational responsibility considers persistent pollution, changes to recharge and ecosystem functions, and delayed impacts. These principles are especially

relevant in contexts where institutional mandates are divided or some groups have limited access to information, as documented in Indonesian river-basin studies (Renaldi & Frinaldi, 2022; Binada, 2023; Putri et al., 2024).

These questions are not satisfied by technical rigor alone. Sarewitz (2004) cautioned that more scientific evidence can intensify environmental controversy where stakeholders differ over values and problem definitions. Cash et al. (2003) linked the effectiveness of knowledge systems to their credibility, salience and legitimacy. Participation research adds a practical qualification: participation improves decisions most reliably under meaningful institutional conditions, rather than simply by inviting comments after an option has already been chosen (Reed, 2008; Newig et al., 2023). Contemporary analyses also warn against assuming that nominal inclusion guarantees the influence of community or Indigenous knowledge on water governance (Kasuri et al., 2026).

From an ethics perspective, a scientifically plausible attribution can still support an unfair policy if uncertainty is borne disproportionately by vulnerable communities. Equally, an insistence on perfect source apportionment could defer reasonable precaution when plausible harm is serious and monitoring capacity is weak. These are not opposing reasons to disregard evidence. They require explicit recognition that administrative action can be proportionate to the risk while the scientific diagnosis continues, provided that reasons, alternatives, safeguards, and opportunities for review remain transparent.

DISCUSSION

An accountability framework for translating catchment evidence into policy

The combined evidence shows the limits of treating scientific monitoring as a pipeline from measured value to self-evident policy. Water-quality interpretations are conditional on source mixtures, spatial coverage, sampling time and stated uncertainty; administrative decisions additionally depend on law, public values and institutional capacities (Ostrom, 2009; Kotamäki et al., 2024). Indonesian watershed studies demonstrate why coordination, information access and stakeholder representation matter alongside technical diagnosis (Pambudi, 2019; Sulistyaningsih et al., 2021; Massiri et al., 2025). A responsible evidence-to-decision process therefore needs safeguards at each transition from an agreed public problem to analysis, appraisal, authorization and subsequent review.

Table 4 and Figure 1 present the proposed evidence-to-decision accountability pathway. It is designed to prevent a scientific indicator from becoming a policy claim without an auditable record of assumptions, alternative explanations, relevant law, affected groups and reasons for action. The framework consolidates established ideas in adaptive and participatory governance around the distinct interpretive difficulty of environmental source attribution. It is a normative synthesis; neither its stages nor its governance benefits have been validated empirically.

Table 4. Proposed six-stage evidence-to-decision accountability pathway for tropical watershed governance

Stage	Key evidence or activity	Accountability / ethical safeguard	Decision output
1. Co-define the problem	Policy objective, affected users, legal mandate and catchment boundary	Record who set the question and whose concerns were excluded	Public decision question
2. Diagnose the catchment	Lithology, mineralogy, land cover, hydrograph and monitoring locations	Disclose site-selection limits and baseline assumptions	Catchment evidence map
3. Attribute and qualify	Major ions, source hypotheses, hydrological states and uncertainty	Separate measured values from inferred causes; document alternatives	Confidence-qualified diagnosis
4. Appraise responses	Applicable standards, risks, costs, benefits and alternatives	Assess distributional impacts and proportionality	Reasoned policy options
5. Deliberate and decide	Expert analysis, local knowledge, affected groups	Provide accessible explanation and meaningful opportunity for challenge	Documented decision and responsibilities

	and authorized decision-makers		
6. Monitor and revise	Follow-up conditions, seasonal indicators, trigger points and grievances	Publish outcomes and rules for revising failed assumptions	Adaptive corrective-action loop

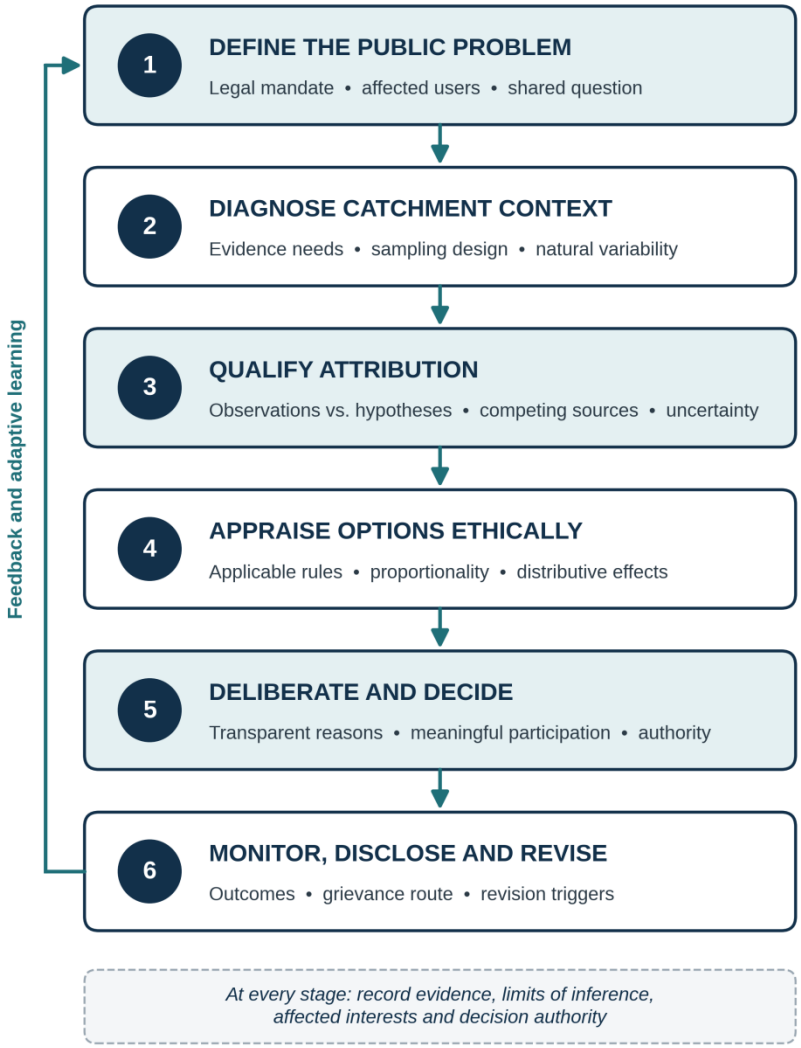

Figure 1. Proposed six-stage evidence-to-decision accountability pathway (author synthesis; not empirically validated).

Stage 1–2: define the decision before collecting more indicators

The first stage asks what public decision needs to be made, which authority may make it and who could be harmed by either action or inaction. A general request for 'better water-quality data' is insufficient to design monitoring that distinguishes causes and supports practical action. Objectives may include protecting drinking-water supplies, assessing an industrial discharge, targeting agricultural runoff controls or understanding a seasonal water-quality problem. Each has different evidential requirements and different legal consequences. Early engagement with relevant communities can reveal uses of water and exposure patterns that official monitoring networks miss, while a clear record should prevent participation from being reduced to symbolic consultation (Maya Jariego, 2024; Tengö et al., 2014).

The second stage establishes a physical catchment model. A map of lithological units is combined with mineralogical characteristics, landscape condition, groundwater recharge and discharge pathways, land use, likely pressures and accessible sampling points. Upstream–downstream comparisons must be justified by flow connectivity rather than proximity alone. For a small volcanic catchment, fresh and weathered volcanic materials

can differ in reactivity; hydrochemical conditions will also reflect residence time, soil gases and groundwater contributions. This physical diagnosis should guide stratified monitoring before management draws conclusions about human influence. In doing so, the framework uses geological knowledge to improve the design of evidence rather than to assign a simple natural-versus-anthropogenic label.

Stage 3–4: distinguish observation, explanation and justified intervention

The third stage records competing causal accounts. Suppose a downstream station has higher dissolved Ca, bicarbonate and electrical conductivity than an upstream station. One hypothesis concerns different rock or sediment mineralogy; others concern longer groundwater contact, irrigation return flows, evaporation, or input from a separate tributary. The observation alone cannot rank these hypotheses. Repeated measurements, major-ion consistency, groundwater information, discharge and land-use documentation can increase discrimination, but uncertainty remains if relevant end-members or event conditions are missing. The appropriate output is a diagnosis qualified by confidence and data gaps, not an unqualified declaration of source or responsibility (Gaillardet et al., 1999; Duvert et al., 2020).

The fourth stage explicitly separates interpretation from intervention. Technical analysts should distinguish measured thresholds, estimated environmental pressure, plausible causal contribution and statutory violations. Decision-makers can then compare response options against the applicable legal objective, the severity and reversibility of harm, the likelihood of exposure, and the distribution of costs. Where evidence is incomplete but consequences may be serious, temporary monitoring or precautionary protection may be defensible if transparently justified. Conversely, irreversible restrictions on a particular group should not be based on weak attribution of the source when reasonable alternative explanations remain. The framework does not prescribe a single precautionary threshold; it requires decision-makers to explain the standard of evidence and why it is proportionate to the measure considered.

Stage 5–6: participation and revision are part of evidence quality

The fifth stage treats transparency and participation as part of the evidentiary chain. A technical report should describe sampling periods, analytical quality controls, uncertainty, and alternative causes in language that affected groups can question. Local knowledge about intermittent springs, dry-season withdrawals, prior land uses or episodic discharges may help identify sampling gaps, without being treated as interchangeable with laboratory measurements. The multiple-evidence-base approach of Tengö et al. (2014) provides a rationale for respecting different knowledge systems and makes explicit how each contributes to the evaluation. The governance literature also indicates that power-sharing arrangements can matter more for environmental outcomes than formal participation alone (Newig et al., 2023).

The sixth stage closes the loop. A management decision should specify expected changes, monitoring periods, update triggers and responsibility for responding when predictions are wrong. Monitoring for adaptive management differs from routine condition reporting in that it tests the assumed link among a pressure, a stressor, and an outcome (Stoffels et al., 2024). Catchment responses may lag interventions because of storage in soils, aquifers or reservoirs, so the review period should correspond to plausible travel times and seasonal cycles. Governance that is responsive to new evidence is more defensible than governance that preserves initial attribution simply because a policy has already been adopted (Moore et al., 2024).

Lessons from documented Indonesian cases and transferability to small tropical watersheds

The six-stage framework can be examined against published Indonesian cases without representing them as original field research. Renaldi and Frinaldi (2022) reported constraints in public information access and intersectoral coordination in the Batang Arau watershed; Sulistyaningsih et al. (2021) identified governance asymmetries in Brantas policy arrangements; and Binada (2023) described tensions and productive interactions between state institutions and civil society in the Brantas basin. These cases support the need to specify decision authority, acknowledge affected publics and keep the evidence trail open. They do not demonstrate that the six-stage pathway would, by itself, resolve such problems.

Mulyawan et al. (2022) examined the Krueng Aceh watershed through biophysical change, stakeholder mapping and policy implementation; their analysis provides an example of why biophysical indicators and institutional responsibilities must be considered together. Work on Citarum connects multi-stakeholder coordination and environmental justice, including concerns about marginalized actors' participation (Abdillah et al., 2024; Putri et al., 2024). In the Poso watershed, Massiri et al. (2025) found that limited knowledge of formal rules and low organizational participation constrained the conversion of community social capital into collective conservation action. These published findings illustrate policy-use challenges but are not new observations made by this review.

For future applications in small volcanic watersheds, such as candidate catchments in Gorontalo, environmental monitoring would need to connect lithological context, groundwater pathways, land use and seasonal hydrology to specific public decisions. This is a proposal for field and governance validation, not a hypothetical case presented as empirical results. Such validation should examine actual monitoring files, government decisions and stakeholder accounts, comparing what evidence was available, how uncertainty was described, who participated and whether decisions were revised when new evidence emerged.

Implications, distinct contribution and limitations

Three practice implications follow from the synthesis. First, environmental reports should distinguish measurement, causal interpretation, confidence, alternative explanations and applicable standards rather than presenting them as interchangeable. Second, agencies should define decision questions and involve relevant publics before selecting indicators or sampling locations. Third, public records should explain who may authorize action, how monitoring and water-quality information is shared, and what would trigger reassessment. Indonesian examples suggest these steps are pertinent to coordination and participation challenges, but further research is necessary to establish whether the framework improves actual governance outcomes (Renaldi & Frinaldi, 2022; Putri et al., 2024; Massiri et al., 2025).

The proposed accountability pathway differs from generic calls for interdisciplinary management in its emphasis on source attribution and the status of geochemical evidence. It asks specifically when a measured ion concentration can support a claim about weathering, when it can support a claim about human pressure, and when neither inference is warranted. It then links those limits to duties of explanation, proportionality, participation and review. Existing work on adaptive science–policy frameworks is an important foundation (Kotamäki et al., 2024), as is the broader shift toward flexible basin governance (Moore et al., 2024). The contribution here is a focused interpretive protocol for geological and hydrogeochemical information rather than a claim to have invented the underlying ethics or governance principles.

The review is purposive, not exhaustive, and the lack of a fully retained retrieval log prevents a reproducible count of all records assessed. Its conclusions cannot estimate how often Indonesian institutions misinterpret scientific indicators, rank policy effectiveness, attribute a specific pollution event to any actor or demonstrate the effects of the proposed framework. Some physical-process sources are international and may not transfer directly to Indonesian catchments. The legal analysis identifies official instruments and amendment status but is not a doctrinal opinion. Future validation should analyse real policy documents and monitoring records, include stakeholder perspectives, and test whether each framework stage improves transparent reasoning and equitable decisions.

CONCLUSION

Watershed governance requires more than technically sound measurements. The Indonesian studies reviewed here document challenges involving institutional coordination, access to information, participation and the relationship between physical catchment conditions and administrative action. Scientific evidence is most useful when decision-makers distinguish observations from causal interpretations, account for uncertainty, justify action under relevant law and consider how costs and benefits are distributed.

The six-stage evidence-to-decision accountability pathway is a conceptual contribution that integrates these safeguards into a transparent sequence of problem definition, catchment diagnosis, uncertainty assessment,

ethical appraisal, deliberation and adaptive review. It offers a structured starting point for Indonesian tropical watersheds, but its practicality and effectiveness must be assessed through implementation studies, monitoring records and stakeholder evaluation.

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