Socio-Technical Control Architecture for Urban Spring Systems Under Environmental Stress

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Abstract: Urban springs in secondary cities of Indonesia are experiencing accelerating degradation amid fragmented governance structures, yet are rarely conceptualized as decentralized environmental systems with systemically identified disturbance components and control mechanisms. This study develops a socio-technical engineering framework based on control system logic to analyze the interaction between water quality pressures and governance capacity in urban spring systems in Probolinggo City, East Java. The study employs a comparative case study design with a mixed-methods approach integrating physicochemical analysis and institutional analysis. Data were obtained from Mayor Regulation Number 38 of 2023, structured field observations (December 5, 2025), and 2024 laboratory monitoring results from six springs. Measurement results indicate nitrate exceedances of up to 65.9 mg/L and iron of up to 33.9 mg/L compared to the quality standards of Minister of Health Regulation No. 32 of 2017, indicating significant environmental disturbances at several locations. Drawing on the collaborative governance model by Chris Ansell and Alison Gash and the Institutional Analysis and Development (IAD) framework developed by Elinor Ostrom, governance is interpreted as a feedback control layer within a closed socio-technical system. The findings reveal alignment patterns between governance strength and relative pressure intensity. The contribution of this study lies in the reframing of governance as an internal control mechanism that influences the stability and risk-buffering capacity of decentralized spring systems with limited redundancy.

Keywords: Urban Springs; Collaborative Governance; Environmental Stress; Water Qality; IAD Framework; Bibliometrics

INTRODUCTION

Decentralized water sources such as urban springs represent micro-scale environmental infrastructure systems characterized by limited redundancy and weak control feedback mechanisms. Unlike centralized water supply systems equipped with treatment facilities, distribution networks, and standard quality control protocols, urban springs operate as low-protection nodes directly exposed to anthropogenic loads, land-use changes, and geochemical mobilization processes. From a systems engineering perspective, these springs can be modeled as high-exposure, low-reliability components within the broader urban water system.Previous research on water resource management indicates that water system failures are rarely caused by physical scarcity alone, but rather by weak integration between technical mechanisms and institutional governance (Pahl-Wostl, 2007). Additionally, research by Mingaleva et al. (2023) demonstrates a significant increase in water governance research since the

adoption of the Sustainable Development Goals, particularly SDG 6, yet the focus remains predominantly on large-scale systems such as river basins, reservoirs, and centralized urban water systems. Meanwhile, small-scale water sources such as urban springs receive relatively little attention within quantitative engineering frameworks, particularly in integrating water quality variables with institutional control capacity.

From a systems engineering standpoint, urban springs can be categorized as environmental nodes with direct exposure to land-use changes, domestic runoff, liquid waste infiltration, and the mobilization of chemical elements such as nitrates and iron. High nitrate concentrations are generally associated with domestic and agricultural activities, while iron levels exceeding threshold limits may result from geochemical conditions or surrounding environmental disturbances (Cakir et al., 2020; Yang et al., 2016). Within the water quality engineering approach, such conditions should trigger control mechanisms based on periodic monitoring of physical and chemical parameters (Prasetyo et al., 2024). However, in decentralized systems, technical responses do not always occur automatically, as they are highly influenced by institutional structures, oversight mechanisms, and the capacity of local actors.

This aligns with findings by Ansell & Gash (2008) which demonstrate that the effectiveness of common resource management is strongly influenced by initial conditions, institutional design, facilitative leadership, and inter-actor interaction processes. Within the Institutional Analysis and Development framework, actor behavior in an action arena is shaped by biophysical conditions, community attributes, and prevailing formal and informal rules (Cole, 2017).

Despite the acknowledged importance of governance, most institutional studies remain qualitative and do not operationalize governance capacity into measurable engineering variables. Conversely, water quality studies typically quantify contamination parameters but treat institutional arrangements as external factors outside the analytical model. This disciplinary separation has produced a methodological gap: the absence of a quantitative engineering model linking pollution intensity with institutional control capacity in decentralized water systems.

This condition is evident in the urban springs of Probolinggo City, East Java. Laboratory monitoring data from 2024 indicate that several locations have nitrate concentrations of up to 65.9 mg/L and iron levels reaching 33.9 mg/L, exceeding the thresholds established in Minister of Health Regulation No. 32 of 2017. At the same time, governance structures across the springs show significant variation, ranging from institutional voids to multi-stakeholder collaborative arrangements institutionalized through Mayor Regulation Number 38 of 2023. This variation provides a natural experimental environment for testing whether measurable levels of environmental stress correlate with measurable governance capacity, and whether this interaction can be expressed within a risk-based engineering framework.

Based on this background, this study develops an integrated socio-technical engineering framework for managing urban springs under environmental pressure. Although the literature on water quality and water resource governance has grown significantly, most research continues to treat the biophysical and institutional dimensions as separate analytical domains. Water quality studies generally emphasize the measurement of physicochemical parameters and compliance with quality standards, while governance research focuses more on institutional design, actor participation, and collaborative processes. From a systems engineering perspective, this separation produces an incomplete system representation, as institutional control mechanisms are not modeled as part of the same system architecture as the physical subsystem. Consequently, the relationship between environmental pressure signals and institutional response capacity has not been analyzed in an integrated manner within a single system framework.

In decentralized water systems with low redundancy such as urban springs, failures in control mechanisms can accelerate the propagation of disturbances toward system outputs in the form of water quality degradation. Unlike centralized systems that possess layered treatment and control mechanisms, urban springs operate as environmental nodes with direct exposure to anthropogenic

loads and land-use changes. In this context, governance capacity can be understood not merely as administrative regulation, but as a control layer that functions to detect, respond to, and dampen environmental disturbances through monitoring mechanisms, actor coordination, and rule enforcement.

Based on the collaborative governance framework developed by Chris Ansell and Alison Gash and the Institutional Analysis and Development (IAD) framework of Elinor Ostrom, actor behavior in an action arena is influenced by biophysical conditions, community attributes, and formal and informal rules. However, explicit integration between water quality parameters as disturbance signals and governance configurations as control mechanisms has not been extensively developed from an environmental systems engineering perspective. This gap indicates the need for an analytical architecture that positions governance as an internal component within the socio-technical control system, rather than as a standalone external variable.

The novelty of this research lies in the development of a socio-technical engineering framework that integrates water quality pressures and governance capacity into a single conceptual model based on closed-loop control system logic. This study does not develop a predictive hydrological model, but rather offers a systems-based interpretive approach to understanding how variations in institutional control configurations influence the intensity of environmental disturbance propagation in decentralized spring systems. In doing so, this study extends the perspective of environmental systems engineering by incorporating the institutional control dimension as part of system performance and stability.

LITERATURE REVIEW

Biophysical Pressures and Water Quality in Decentralized Systems

Water quality in groundwater and spring systems is influenced by a combination of geohydrological factors and anthropogenic pressures (Okiemute, 2025a). Nitrogen loads and microbiological contaminants are the primary indicators of water quality degradation in shallow aquifer systems (Banseka & Tume, 2024; Yang et al., 2016). Shtull-Trauring et al. (2025) in their research on intensive monitoring, demonstrate that agricultural activities and domestic runoff can significantly increase nutrient and pathogen concentrations, thereby reducing the reliability of water supply systems. Water quality evaluations in urban areas also show that land-use pressures correlate with declining groundwater quality (Mohamed et al., 2014). These findings affirm that decentralized water systems are highly sensitive to external disturbances and require evaluation approaches based on quantitative indicators.

Climate Variability and Hydrological Uncertainty

Climate change amplifies uncertainty in water availability and quality through changes in rainfall patterns, temperature, and drought (Barkmann et al., 2017; Körner et al., 2005; Sitanggang, 2025). Long-term hydrological simulations indicate that variations in aquifer recharge and river flow are strongly influenced by future climate scenarios (Brussolo et al., 2021; Dubois et al., 2021). The integration of multi-source climate models in seasonal flow projections can improve the accuracy of water availability predictions (Baker et al., 2021). This uncertainty directly affects the stability of decentralized water systems, particularly in drought-prone areas (Pokharel et al., 2024; Scarsini et al., 2024). Therefore, water system evaluation must account for the dimensions of risk and long-term variability.

Monitoring Approaches and Quantitative Models

Advances in monitoring technology and modeling have strengthened the analytical capacity of water resource systems. The use of Google Earth Engine-based platforms enables efficient drought mapping and spatial trend analysis (Alzurqani et al., 2024). Integrated hydrological modeling approaches are also used to simulate sedimentation and land-use change scenarios (Patault et al., 2021). In addition, the integration of spatial water budgets with streamflow depletion functions provides a quantitative framework to support stakeholder-based decision-making (Foglia et al., 2013). In the context of water

quality, systematic monitoring of pathogens and chemical parameters forms the basis for developing water safety surveillance systems (Do Nascimento et al., 2023; Duncan et al., 2025).

The Gap in Biophysical and Governance Integration

Water security and urban poverty research indicates that social vulnerability and management capacity influence access to and quality of water (Adams et al., 2020). Participatory and adaptive approaches to water management have also been developed in response to climate change and resource pressures (Azhoni & Goyal, 2018; Sen & Kansal, 2019). However, most of these studies employ qualitative or multi-criteria approaches without operationalizing institutional variables in the form of measurable indices (Valente et al., 2021).

Thus, although both the biophysical and social dimensions are recognized as equally important in water resource management, their integration within a single risk-based system evaluation framework remains limited. Few studies have developed integrated quantitative models that combine water quality index calculations, hydrological variability, and governance capacity as control subsystems within decentralized water systems. This methodological gap forms the basis for developing the socio-technical engineering approach in this study.

Table 1. Bibliometric Analysis and Identification of Methodological Gaps

S pring	p H	Tem perature (°C)	Tu rbidity (NTU)	T DS (mg/L)	N itrate (mg/L)	N itrite (mg/L)	I ron (mg/L)	Ma nganese (mg/L)
Ja lil	7 .2	28.8	<M DL	7 90.0	6 5.9	0 .00	0 .83	<M DL
S entong	7 .2	28.8	3.2	5 75.0	2 9.5	2 .00	< MDL	<M DL
K asbah	7 .3	29.2	<M DL	4 73.3	2 2.3	0 .00	2 9.9	<M DL
Pi nang	7 .0	27.2	<M DL	5 00.0	< MDL	< MDL	3 3.0	0.01
Pi lang	7 .2	27.2	0.5	5 55.0	< MDL	< MDL	3 3.9	0.01
P acar	7 .0	29.2	<M DL	6 61.7	3 1.5	0 .05	< MDL	<M DL
Ja lil	7 .2	28.8	<M DL	7 90.0	6 5.9	0 .00	0 .83	<M DL

A bibliometric analysis of publications on groundwater management and water governance from 1996 to 2026 reveals a significant increase in the number of publications, from an average of two articles per year during the period 1996–2005 to twenty-eight articles in 2025. This increase reflects growing global attention to water resource sustainability, particularly following the strengthening of the Sustainable Development Goals agenda, especially SDG 6 (Nugraheni & Islami, 2024). Publications are dominated by journals in the fields of water and environmental management such as Water, Sustainability, and the Journal of Environmental Management, indicating that research remains focused on hydrological, sustainability, and environmental management aspects.

Co-occurrence analysis of keywords identifies five main clusters: water resource management at 41 percent, climate change adaptation at 22 percent, governance and institutions at 18 percent, integrated water resources management at 12 percent, and urban water at 7 percent. Although water quality and water supply themes fall within the category of motor themes with high levels of relevance and conceptual maturity, terms specifically referring to urban springs appear in only three documents, or approximately 1.7 percent of total publications. Furthermore, an explicit linkage between water quality parameters and governance capacity is found in only seven documents, or approximately 4.1 percent.

Thematic mapping shows that water quality and water supply topics have developed conceptually, while governance, stakeholder, and water management themes remain in the category of basic themes that are relevant but not yet strongly integrated into quantitative models. This condition indicates that although the biophysical and institutional dimensions are both widely discussed, their integration within a single engineering-based analytical framework remains limited.

These findings confirm the existence of a methodological gap in the environmental engineering literature, particularly regarding the development of system evaluation models that combine water quality pressures and institutional control capacity for decentralized spring systems under environmental stress.

Socio-Technical Systems Engineering Modeling Framework

This study regards urban springs as a closed-loop socio-technical control system, as illustrated in Figure 1. Within this framework, environmental pressures such as nitrate and iron concentrations, as well as organic matter loads, are positioned as external disturbances (disturbance inputs) that affect the physical subsystem, namely the hydrogeochemical node of the spring.

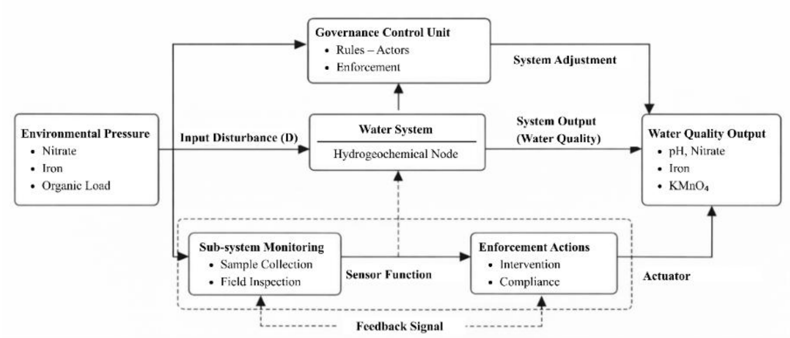

Figure 1. Socio-Technical Control System Model for Decentralized Urban Spring Management

The spring system functions as a physical subsystem that produces outputs in the form of measurable water quality parameters (pH, TDS, nitrate, iron, $KMnO_4$, microbiological indicators). The governance mechanism is positioned as the control unit, operating through three main components: rules, actors, and enforcement mechanisms.

Water quality monitoring activities (laboratory sampling and field inspections) function as the sensing mechanism that detects changes in system conditions. When quality threshold exceedances occur, a feedback signal is generated to trigger an institutional response in the form of administrative, social, or moral intervention.

Accordingly, governance strength is understood as the system's capacity to dampen the propagation of environmental disturbances toward system outputs. The stronger the control and feedback mechanisms, the greater the system's ability to maintain water quality stability.

Figure 1 Illustrates environmental pressures as disturbance inputs, the governance control unit as an adaptive controller, the monitoring subsystem as a sensing function, and enforcement actions as actuators, with water quality output as the system response.

RESEARCH METHODOLOGY

Research Design

This study employs a comparative case study design with a mixed-methods approach integrating descriptive quantitative analysis and qualitative institutional analysis. The quantitative approach is used to evaluate the physicochemical conditions of six urban springs in Probolinggo City based on 2024 laboratory data compared against the quality standards of Minister of Health Regulation No. 32 of 2017. This analysis aims to identify the level of environmental pressure through exceedance patterns of key parameters such as nitrate, nitrite, and iron.

Subsequently, a qualitative approach is applied through an embedded comparative case study to analyze variations in governance configurations at each spring location, including the actors involved, applicable rules, monitoring mechanisms, and forms of rule enforcement. Integration of both approaches is carried out at the interpretation stage to explain how biophysical pressures interact with institutional capacity and collaborative mechanisms in water resource management.

This approach was selected because it enables the representation of spring systems as a unified socio-technical entity, in which water quality parameters are treated as system outputs and governance as a control mechanism that influences responses to environmental disturbances. Integration of both

dimensions is conducted at the interpretation stage to maintain the coherence of the system architecture.

Case Study Sites and Sampling Logic

This study employs a comparative case study design with a theoretical variation approach to capture differences in governance capacity across decentralized spring systems. Four springs were purposively selected for governance analysis: Umbul or Ganesha, Gayam, Sumber Wetan, and Sentong. This selection was based on identified variations in governance types, namely governance voids, community-based management, and collaborative governance. This purposive approach enables in-depth exploration of differences in institutional control mechanisms within the context of similar environmental pressures.

To establish a biophysical pressure baseline, monitoring data from six springs available at the Technical Implementation Unit of the Environmental Laboratory were used, namely Jalil, Sentong, Kasbah, Pinang, Pilang, and Pacar. These six locations provide cross-site comparability in terms of physical and chemical indicators, enabling the classification of relative pressure levels across locations.

This approach yields two layers of analysis: governance variation across four main cases and comparison of water quality pressure levels across six monitoring locations.

Data Sources

Data were obtained from the following sources:

Table 2. Documentary: Perwali No. 38/2023 (full text analysis of protection zoning, DLH mandate, enforcement provisions)

Parameter	Unit	Observed Value	Indonesian Standard*	WHO Guideline
pH	–	7.0	6.5–8.5	6.5–8.5
Turbidity	NTU	1.0	≤25	≤5
TDS	mg/L	305	≤1000	≤1000
Nitrate (as N)	mg/L	5.3	≤10	≤50
Nitrite (as N)	mg/L	0.96	≤1	≤3
Iron (Fe)	mg/L	0.053	≤1	≤0.3
Manganese (Mn)	mg/L	0.039	≤0.5	≤0.4
Total coliform	CFU/100 mL	10	≤50	0
E. coli	CFU/100 mL	0	0	0
Detergent	mg/L	0.10	≤0.05	–
Organic matter($KMnO_4$)	mg/L	25.4	≤10	–

Field observations: Structured walkthroughs (5 December 2025) documenting physical conditions, usage patterns, institutional artifacts (signage, infrastructure), actor presence

Laboratory: UPT Environmental Lab baseline (2024; Table 1); UPT and PT Mitralab Buana comprehensive Sentong assessment (25 September 2024; Table 2)

Standards: Permenkes No. 32/2017 (hygiene-sanitation thresholds); WHO drinking-water guidelines

Integration of quantitative and qualitative analysis was conducted at the interpretation stage through a systemic triangulation approach. Laboratory data were used to identify disturbance intensity, while governance analysis was used to characterize control configurations. Both were subsequently synthesized into a governance–stress typology to identify system alignment patterns.

Table 3. Data Analysis

Spring	Governance Type	Key Actors	Rules-in-Use	Monitoring	Enforcement	Water Quality Stress
Umbul (Ganesha)	Governance vacuum	None	None	None	None	High
Gayam	Community-based	LPM, residents	Informal norms	Irregular	Social	Medium
Sumber Wetan	Informal community	Residents	Customary practice	Occasional	Moral	Medium
Sentong	Collaborative governance	Pokdarwis, DLH, community	Formal agreement	Routine	Admin + social	Low
Jalil	Weak community	Local users	Informal use	Minimal	None	High
Pacar	Fragmented	Local users	Informal	Minimal	None	High

Governance coding was conducted using a deductive–inductive thematic approach. Analytical categories followed IAD elements (rules-in-use, actors, action arenas) and collaborative governance constructs (starting conditions, institutional design, leadership, interaction process). These categories were applied to regulatory documents, field observations, and interview notes to identify governance configurations across sites.

Stress classification: Relative stress levels (High/Medium/Low) based on exceedances vs. Permenkes 32/2017:

High: ≥2 major parameters exceed standards by >2× (nitrate, iron, $KMnO_4$)

Medium: 1 parameter exceeds or multiple approach thresholds

Low: No exceedances in priority parameters

Triangulation: Cross-validation across lab data (quantitative stress), field observations (qualitative governance), Perwali text (formal rules), yielding governance-stress typology.

Physicochemical Assessment Framework and Quality Standard Compliance

Water quality assessment was conducted using 2024 laboratory data from the UPT Environmental Laboratory across six urban springs. Parameters analyzed include pH, temperature, turbidity, Total Dissolved Solids (TDS), nitrate (NO_3^-), nitrite (NO_2^-), iron (Fe), and manganese (Mn).

Technical evaluation was carried out through a threshold-based compliance assessment approach referencing Minister of Health Regulation No. 32 of 2017 on Water Quality Standards for Hygiene and Sanitation Purposes.

The parameters that form the primary focus of environmental pressure analysis are:

Nitrate (quality standard: 10 mg/L)

Nitrite (quality standard: 1 mg/L)

Iron/Fe (quality standard: 1 mg/L)

The selection of these three parameters is based on:

Public health relevance

Identified patterns of quality standard exceedance

Significance as indicators of anthropogenic pressure

These three parameters were selected because they represent the most consistently occurring indicators of anthropogenic pressure in routine monitoring and have direct implications for health risk and the stability of decentralized water systems.

Ratio Formula

To assess the relative pressure level of each parameter, a simple compliance ratio is used as follows:

$$R_i = \frac{C_i}{S_i}$$

Where:

R_i= Pressure ratio of parameter i

C_i= Measured concentration of parameter i

S_i= Quality standard of parameter i

Interpretation:

$R_i < 1 \rightarrow$ meets quality standard

$R_i = 1 \rightarrow$ exactly at threshold

$R_i > 1 \rightarrow$ exceeds quality standard

Parameters with values below the Method Detection Limit (MDL) are treated as zero for the purposes of conservative comparative interpretation.

Environmental Pressure Classification Logic

The classification of water quality pressure levels in Table 3 is not based solely on mathematical aggregation, but employs an interpretive approach based on:

Exceedance patterns of priority parameter quality standards

Spatial exposure intensity (settlement density and surrounding activities)

Monitoring capacity and rule enforcement

Accordingly, the High, Medium, and Low-Pressure categories in Table 3 are positioned as governance-relevant environmental stress, rather than as a purely composite chemical index.

This approach aligns with the Institutional Analysis and Development (IAD) framework, which emphasizes the interaction between biophysical conditions and institutional arrangements in determining the dynamics of resource management responses.

This classification is comparative across locations and is not intended as an aggregative chemical index, but rather as a systemic categorization for identifying the level of disturbance propagation relative to control capacity.

RESULTS

Environmental Stress Signals

Within the socio-technical control system framework (Figure 1), water quality parameters represent system outputs influenced by the intensity of environmental disturbances. Nitrate and iron concentrations exceeding quality standards indicate high disturbance propagation at locations with weak control capacity.

Water quality monitoring needs to be conducted continuously because physical and chemical parameters such as pH, TDS, nitrate, nitrite, and iron (Fe) serve as key indicators of water suitability for domestic needs and environmental sustainability. The data in Table 1 are presented as a baseline overview of water quality conditions to identify potential pollution pressures and support the planning of sustainable water resource management.

Note: Bold = exceeds Permenkes 32/2017 standards. MDL = method detection limit.

Table 1 presents the baseline water quality conditions from the 2024 UPT Environmental Laboratory tests at six springs. The measurement results indicate that pH values remain within the neutral range of 7.0–7.3, and the Total Dissolved Solids (TDS) parameters still meet the required quality standard of less than 1000 mg/L. However, several parameters show significant pollution pressure. Nitrate concentrations were detected to exceed the quality standard of 10 mg/L at the Jalil Spring (65.9 mg/L), Sentong (29.5 mg/L), Kasbah (22.3 mg/L), and Pacar (31.5 mg/L) springs. Furthermore, iron (Fe) levels also surpassed the standard limit of 1 mg/L at the Kasbah (29.9 mg/L), Pinang (33.0 mg/L), and Pilang (33.9 mg/L) springs, while Jalil

Spring showed a value nearing the threshold at 0.83 mg/L. The nitrite parameter was also recorded to exceed the quality standard at Sentong Spring with a concentration of 2.0 mg/L, higher than the standard limit of 1 mg/L. This condition indicates a potential decline in water quality at several locations that requires attention in water resource management.

Table 2 details Sentong's comprehensive assessment (25 September 2024). Microbiological compliance (E.coli = 0 CFU/100mL; total coliform = 10 ≤50) contrasts with organic matter exceedance ($KMnO_4$ 25.4 mg/L vs. 10mg/L), signaling ongoing domestic loading despite governance strengths.

Based on Table 2, the results of the comprehensive assessment of Sentong Spring on September 25, 2024, indicate that most physical-chemical and microbiological parameters remain within national quality standards and WHO guidelines. The values for pH (7.0), turbidity (1.0 NTU), TDS (305 mg/L), nitrate (5.3 mg/L), nitrite (0.96 mg/L), iron (0.053 mg/L), and manganese (0.039 mg/L) all meet the established standards, suggesting relatively good and stable baseline water quality. From a microbiological perspective, the non-detection of E. coli (0 CFU/100 mL) and a total coliform count of 10 CFU/100 mL (still below the national threshold of ≤50 CFU/100 mL) reflect good compliance with health aspects, although not fully meeting the WHO guideline requiring zero total coliform.

However, there are indications of significant organic pollution pressure, as indicated by the high organic matter content ($KMnO_4$) of 25.4 mg/L far exceeding the national standard (≤10 mg/L) and a detergent level of 0.10 mg/L, which surpasses the permissible limit (≤0.05 mg/L). This condition suggests that domestic wastewater loads in the vicinity of the spring remain substantial. Therefore, although water governance and source protection have been relatively effective in controlling microbiological contamination, efforts to manage household waste and reduce organic inputs must be strengthened to ensure the long-term sustainability of Sentong Spring's water quality.

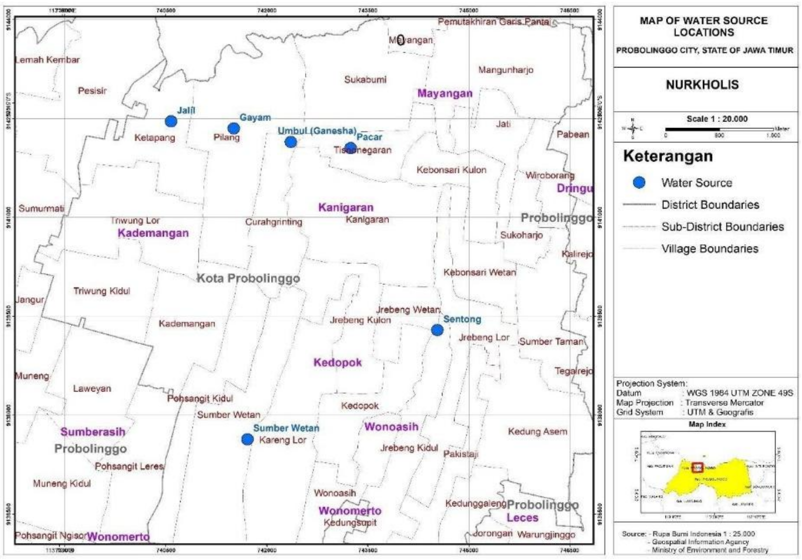

Figure 2. Study Area and Locations of the Six Monitored Springs in Probolinggo City, East Java, Indonesia, Color-coded by Governance Typology

Figure 2 illustrates the six monitored springs in Probolinggo City follow a distinct spatial zoning pattern. In the northern–coastal region (Mayangan & Kademangan Districts), springs such as Jali, Gayam, Umbul/Ganesha, and Pacar are clustered in dense residential and commercial zones, indicating higher exposure to anthropogenic pressure from land-use change and domestic water demand. Springs in the central zone (Kanigaran & Kedopok Districts) lie in a peri-urban transition area, influenced by infrastructure development. In contrast, springs in the southern region (Wonoasih District) experience lower urbanization intensity and more stable environmental conditions. These spatial variations underscore the differing governance contexts and environmental pressures across the city, providing a key basis for examining how management approaches and location affect spring sustainability.

Governance Regimes and Governance-Stress Linkage

Based on the control system model developed, variations in governance regimes reflect differences in the control unit's capacity to respond to disturbance signals. Locations with governance voids demonstrate weak feedback mechanisms, causing environmental disturbances to be transmitted directly to system outputs. Conversely, collaborative models such as that at Sentong demonstrate more effective control and stabilization functions through routine monitoring and rule enforcement.

Table 3 synthesizes governance characteristics with relative stress profiles. Umbul/Ganesha exhibits governance vacuum (no actors, no rules, high stress). Gayam/Sumber Wetan demonstrate community stewardship (informal norms, irregular monitoring, medium stress). Sentong reflects collaborative governance (Pokdarwis-DLH linkage, routine monitoring, relatively lower stress). High-stress sites (Jalil, Pacar) show weak/fragmented arrangements.

As shown in Table 3, the analysis of Probolinggo City's urban springs confirms a direct relationship between governance strength and water quality pressure. Where governance is absent or weak as seen at Umbul (Ganesha) Spring, which lacks key actors, rules, monitoring, and enforcement, and at Jalil and Pacar Springs, which operate under fragmented, informal community arrangements water quality pressure is high. Conversely, Sentong Spring, managed through a formal collaborative model involving multiple stakeholders with routine monitoring and clear enforcement, experiences low pressure. Springs like Gayam and Sumber Wetan, governed by informal community norms and irregular monitoring, fall into a medium-pressure category. Overall, the findings in Table 3 underscore that stronger institutional roles, clear usage rules, consistent monitoring, and effective enforcement significantly reduce water quality pressure.

DISCUSSION

Water Quality Variation as an Indicator of System Pressure

Water quality variation across locations indicates that urban spring systems operate as environmental nodes with differing levels of disturbance propagation. From a systems engineering perspective, parameter exceedances are not merely deviations from quality standards, but represent disturbance intensity that is not fully dampened by the available control mechanisms.

Nitrogen loads in aquatic systems are strongly influenced by the combination of domestic pollution sources and the spatial characteristics of catchment areas (Cakir et al., 2020; Yang et al., 2016). Furthermore, changes in hydrological variability resulting from climate change can amplify fluctuations in groundwater quality and accelerate contaminant propagation (Dubois et al., 2021; Jin & Sridhar, 2012). These findings reinforce the interpretation that the water quality conditions identified in this study are not merely local phenomena, but part of broader system dynamics.

Accordingly, water quality parameter exceedances in this study are interpreted not only as deviations from quality standards, but as disturbance signals within the socio-technical system of spring management.

Governance as a Control Layer in System Architecture

Research findings indicate that locations with active governance characterized by monitoring and inter-actor coordination exhibit relatively more controlled conditions compared to locations with weak governance. This indicates that governance capacity functions as a control layer within the architecture of decentralized spring systems.

These findings indicate that governance functions as an internal control component within the system architecture, rather than as an external administrative factor. When routine monitoring, actor coordination, and enforcement mechanisms operate consistently, the system exhibits closed-loop characteristics with more stable feedback capacity. Conversely, at locations without control mechanisms, the system resembles an open-loop configuration in which environmental disturbances directly affect water quality outputs.

In systems engineering, the distinction between open-loop and closed-loop systems lies in the presence of feedback mechanisms. Locations without routine monitoring exhibit system characteristics resembling open-loop systems, in which environmental disturbances directly affect water quality without corrective mechanisms. In contrast, locations with more active monitoring and coordination exhibit closed-loop system characteristics, in which water quality information is used as the basis for response actions.

The integration of hydrological data into decision-making has long been identified as an important factor in maintaining groundwater system stability (Foglia et al., 2013). Additionally, weak oversight in community-scale water systems increases the risk of contamination and water quality disturbance (Banseka & Tume, 2024; Duncan et al., 2025). Accordingly, this study's findings affirm that governance is not merely an administrative aspect, but part of the control infrastructure that determines system performance.

The governance configurations identified in this study align with the collaborative governance model that emphasizes the importance of starting conditions, institutional design, and facilitative leadership in shaping collaboration effectiveness (Ansell & Gash, 2008). At locations with supportive starting conditions, prior cooperative experience and local organizational capacity strengthen the formation of stable coordination structures. Conversely, at locations with weak facilitative leadership and unclear institutional design, collaborative processes do not develop functionally. From a systems perspective, such variation reflects differences in adaptive control capacity for processing environmental disturbances.

Analysis of the implementation of Perwali 38/2023 also reveals variation in alignment between formal rules (rules-in-form) and actual field practices (rules-in-use). Within the Institutional Analysis and Development (IAD) framework, the interaction between biophysical conditions, community attributes, and institutional rules shapes actor behavior in the action arena (Cole, 2017). At some locations, alignment between formal rules and field practices strengthens the system's control function. However, at other locations, informal norms or de facto open-access conditions indicate a lack of synchronization between regulatory design and implementation, with implications for weakened control effectiveness.

Feedback Dynamics and System Reliability

System effectiveness is strongly influenced by the presence and efficiency of feedback pathways. Monitoring functions as a sensor that enables the system to detect changes in environmental conditions at an early stage. In this study, limited monitoring at several locations has the potential to cause delayed responses to water quality disturbances.

The use of spatial and temporal monitoring technologies has been demonstrated to enhance detection capacity for environmental pressures (Alzurqani et al., 2024; Derdour et al., 2023). Anthropogenic pressures on aquatic systems are often more complex than what is identified through sporadic observation (Okiemute, 2025b; Shtull-Trauring et al., 2025).

Water quality variation across locations in this study can be understood as the result of the interaction between the level of environmental pressure and the efficiency of institutional feedback mechanisms. Systems with clearer feedback pathways tend to possess greater adaptive capacity in responding to disturbances.

In an operational context, rule enforcement mechanisms at several locations exhibit a tiered pattern that can be understood as an enforcement cascade, namely administrative, social, and moral. This layered approach creates redundancy in the control structure and reinforces compliance through a combination of formal instruments and community norms. Further, the tiered distribution of management capacity, with certain locations functioning as capacity centers and others existing in a state of institutional vacuum, illustrates a capacity cascade that influences system reliability levels across locations. This disparity indicates that system stability is determined not only by environmental pressure, but also by the spatial distribution of control capacity.

From a system reliability perspective, decentralized springs with low redundancy are highly dependent on the effectiveness of feedback mechanisms. The absence of monitoring or rule enforcement increases the probability of disturbance propagation without early correction, thereby reducing the system's stability margin. Accordingly, governance variation can be understood as variation in risk-buffering capacity at the level of the environmental node.

Engineering Implications for Urban Spring Risk Management

This study demonstrates that decentralized urban springs are systems with high-risk exposure and limited redundancy capacity. In the context of urban water insecurity in the Global South, water system vulnerability has direct implications for community health and welfare (Adams et al., 2020).

Collaborative approaches to water resource management have been identified as an important strategy for addressing environmental pressures (Azhoni & Goyal, 2018; Sen & Kansal, 2019). However, the findings of this study affirm that collaboration must be operationalized as a structured control mechanism within the system, rather than merely as a coordination forum.

The contribution of this study lies in the development of a socio-technical system model that integrates environmental pressures, governance mechanisms, and water quality responses within a single unified analytical framework. This approach extends the environmental engineering paradigm by incorporating the institutional control dimension as an integral part of system performance, and opens avenues for integration with risk management and system reliability engineering.

Conceptually, this study extends the environmental systems engineering approach by incorporating institutional capacity as an internal control variable within the socio-technical system model. This approach enables the analysis of environmental pressures not merely as chemical or hydrological phenomena, but as the result of interaction between biophysical disturbances and institutional control configurations.

Limitations

Single-period laboratory data limits trend analysis; future monitoring should capture seasonal dynamics. Governance assessment relies on observations rather than extended participant observation or interviews. Stress classification thresholds require validation against health/ecological endpoints.

CONCLUSION

This study demonstrates that water quality variation in urban springs cannot be understood solely as a chemical phenomenon or isolated environmental pressure, but rather as the result of interaction between biophysical disturbances and governance configurations that function as system control mechanisms. In decentralized water systems with low redundancy, exceedances of parameters such as nitrate, BOD, and COD represent disturbance intensity that is not fully dampened by institutional feedback capacity.

Comparative findings across locations indicate that differences in monitoring configurations, actor coordination, and rule enforcement are associated with variation in environmental pressure levels. Locations with more consistent control mechanisms exhibit closed-loop system characteristics, in which disturbance signals are detected and responded to through corrective actions. Conversely, locations with weak control display configurations that approximate open-loop systems, causing environmental disturbances to propagate more readily toward system outputs in the form of declining water quality.

Conceptually, this study extends the environmental systems engineering approach by positioning governance capacity as an internal component within the socio-technical system architecture. This integration enables a more comprehensive understanding of the stability and reliability of urban spring systems, particularly in the context of increasing anthropogenic pressure. Accordingly, improvements in system performance depend not only on physical technical interventions, but also on the strengthening of institutional control mechanisms as part of the overall system design.

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