

Environmental Monitoring Network Optimization for Supporting Targeted Policy-making in Air Pollution Prevention and Control

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Keywords: Environmental Monitoring Network; Air Pollution Prevention and Control; Targeted Policy-Making; Information Efficiency; Governance Evidence Chain

Abstract: Air pollution prevention and control is shifting from total emission control to targeted policy-making, and environmental monitoring networks have gradually evolved from basic technical infrastructures into core information systems supporting scientific decision-making and institutional operation. This study focuses on how to optimize environmental monitoring networks to effectively support targeted policy-making in air pollution control, and conducts a systematic analysis from three interrelated dimensions: theoretical framework, data-model coupling, and decision-making chain restructuring. We emphasize reconstructing the monitoring paradigm based on information efficiency, optimizing the network structure under multi-objective constraints, and establishing an indicator system that converts observational performance into governance performance. On this basis, the study further reveals the critical roles of data quality governance, explicit uncertainty expression, and multi-scale mechanism constraints in constructing the governance evidence chain, and clarifies the supporting mechanisms of monitoring network optimization in promoting targeted pollution identification, evidence-based decision-making, and closed-loop governance. The results show that embedding the optimization of environmental monitoring networks into the governance logic improves the rationality and institutional stability of air pollution prevention and control, while providing a solid information foundation and methodological support for targeted policy-making.

1. Introduction

Against the backdrop of increasingly complex causes of air pollution and refined governance objectives, traditional prevention and control approaches centered on administrative units and average concentration indicators have gradually shown slow responsiveness and poor targeting, thus making targeted policy-making an important direction in contemporary environmental governance^[1]. The role of environmental monitoring networks has undergone a profound transformation, expanding from merely describing environmental conditions to providing critical evidence for pollution identification, source attribution, and policy evaluation. Whether monitoring networks can effectively characterize the spatiotemporal heterogeneity of air pollution and provide robust support

for differentiated control measures is directly related to the effectiveness of targeted policy-making.

Existing studies have largely focused on monitoring technologies or modeling methods, while relatively limited attention has been paid to systematically examining the institutional significance and decision-making value of monitoring network optimization from the perspective of overall governance logic. This constitutes a critical research gap in the decision-making system for air pollution prevention and control. Therefore, this study analyzes three core dimensions: theoretical paradigms, evidence-chain construction, and the restructuring of decision-making mechanisms, and elucidates the foundational role and internal logic of monitoring network optimization in supporting targeted policy-making.

2. Theoretical Framework of Monitoring Network Optimization and Reconstruction of Objective Functions

2.1 Paradigm Shift from “Site Coverage” to “Information Efficiency”

The construction of environmental monitoring networks has long centered on spatial coverage rates and station density, and the evaluation logic has largely focused on the uniform geographic distribution of monitoring units and the formalistic coverage of administrative divisions. With the increasing complexity of contemporary air pollution formation mechanisms and the intensification of spatiotemporal heterogeneity, this paradigm has revealed significant limitations such as information redundancy and insufficient capacity for identifying key processes. By contrast, a monitoring paradigm oriented toward information efficiency emphasizes the contribution of observational activities to pollution identification, process interpretation and decision support. This paradigm regards monitoring networks as information production systems rather than mere collections of data acquisition points, and highlights the effectiveness of observational data in depicting pollution gradients, capturing temporal discontinuities and distinguishing emission-driving patterns.

The value of individual monitoring sites is not determined by physical presence alone, but by the information increment and structural complementarity they generate within the overall network. Thus, the function of monitoring networks is shifting from static descriptions of environmental states to dynamic support for governance judgments, which provides a solid evidence base for targeted policy-making.

2.2 Network Structural Optimization Logic under Multi-objective Constraints

Monitoring network optimization is a systemic decision-making problem embedded in resource allocation challenges, administrative boundaries, and constraints imposed by environmental processes. Structural adjustments face multiple trade-offs, particularly between accuracy enhancement and operational costs, as well as maintenance stability and management feasibility. The logic of network structural optimization requires coordinating the balance between information acquisition efficiency and long-term operational sustainability under resource constraints, so that monitoring units can form hierarchically organized and functionally complementary configurations across different spatial scales.

Constraint conditions arise from fiscal and technical factors, and are also deeply influenced by topography, meteorological patterns, emission spatial patterns and administrative management systems, which determines the observable space and structural flexibility of monitoring networks. In contexts where multiple objectives coexist, optimization does not mean pursuing extreme values for a single indicator, but selecting the feasible solution that maximizes information efficiency within the constraint set. This ensures that the network structure not only reflects the actual

characteristics of pollution processes, but also maintains a high degree of coupling and stable coordination with the governance system.

2.3 Construction of an Indicator System for Translating Observational Performance into Governance Performance

The evaluation of monitoring network optimization effectiveness needs to break away from the constraints of traditional technical indicator systems. It is necessary to integrate observational performance and governance outcomes into a unified analytical framework, and develop an indicator system with clear explanatory mechanisms and strong policy relevance. Such a system presents a logically progressive structure from the observational layer to the information layer and finally to the governance layer.

The observational layer emphasizes data accuracy, continuity and completeness; the information layer focuses on spatial resolution, process sensitivity and multi-source synergy; the governance layer concentrates on the clarity of pollution attribution, the targeting of policy measures and the verifiability of outcome evaluation. These indicators are not independent but embedded within causal chains, which enables the mapping of technical performance onto policy choices and management outcomes. The establishment of such an indicator system helps bridge cognitive discontinuities between monitoring and governance, endows network optimization outcomes with auditability, comparability and feedback capacity, and thus lays a stable and transparent evaluative foundation for targeted policy-making.

3. Construction of an Evidence Chain for Precise Governance Supported by Data Systems and Model Coupling

3.1 Institutional Logic of Monitoring Data Quality and Consistency Governance

As targeted policy-making gradually replaces coarse management as the core orientation of air pollution prevention and control, the function of monitoring data has undergone a fundamental transformation. It has shifted from merely reflecting environmental conditions to serving as critical evidence units that support policy judgment, measure alignment and performance evaluation. This transformation directly requires data quality governance to be institutionalized, systematic and sustainable.

Data quality is no longer confined to technical dimensions such as numerical accuracy or continuity, but also extends to the normativity of data-producing entities, the standardization of data collection processes, the transparency of processing rules and the traceability of data use. This ensures that data remains stable and credible throughout the entire governance chain [2]. The governance logic centered on consistency emphasizes the establishment of coordinated constraints across different monitoring networks, equipment types and management levels in terms of temporal benchmarks, statistical calibers and result presentation, so as to mitigate information deviations caused by technological heterogeneity or institutional fragmentation.

Institutionalized data quality governance not only enhances the comparability and verifiability of monitoring results, but also accumulates governance trust through sustained operation. This enables data to be repeatedly cited and validated in complex policy environments, thus providing a legitimate and stable foundation for model analysis and targeted decision-making.

3.2 Synergistic Constraint Mechanism of Spatial Representativeness and Uncertainty Expression

Under real-world conditions characterized by increasingly complex emission structures and high degrees of heterogeneity in urban spatial forms, observational data obtained from individual monitoring sites can hardly be extrapolated to comprehensively characterize regional environmental conditions. Cognitive biases resulting from insufficient spatial representativeness frequently constitute a major cause of failure in targeted policy-making. The evaluation of spatial representativeness requires an integrated consideration of topographic variation, surface characteristics, meteorological field structures and emission source distributions, so as to rationally define the spatial scope and applicable conditions that observational results can reflect. Boundary clarification is therefore critical before monitoring information enters the decision-making process.

Uncertainty expression plays a crucial constraining role in this process by explicitly presenting factors such as observational errors, biases from model structural assumptions and risks associated with spatial interpolation. This enables decision-makers to clearly understand pollution conditions and recognize the confidence intervals of analytical conclusions. The synergistic mechanism formed by spatial representativeness and uncertainty expression helps prevent the generalization of localized information into overall judgments and avoid the over-interpretation of monitoring results in policy contexts. This further strengthens the robustness and rationality of decision-making processes on the basis of a comprehensive understanding of spatial heterogeneity and epistemic uncertainty.

3.3 Collaborative Modeling Pathways Integrating Multi-scale Data Fusion and Mechanism Constraints

The generation, evolution and dissipation of air pollution exhibit pronounced multi-scale coupling characteristics, where regional transport backgrounds, urban-scale diffusion structures and micro-scale anthropogenic activities overlap across temporal and spatial dimensions. Analyses conducted at isolated scales have inherent limitations in fully revealing the internal mechanisms governing pollution dynamics. The objective of multi-scale data fusion is to integrate monitoring information from diverse sources and resolutions, enabling observations at the regional, urban and local levels to form a coherent and continuous cognitive structure within a unified framework, thus supporting the systematic understanding of pollution processes.

Collaborative modeling pathways emphasize the incorporation of mechanism constraints during data fusion, by embedding atmospheric chemical reaction principles, physical diffusion conditions and emission-driving relationships into model structures. This ensures that analytical processes both assimilate multi-source information and adhere to objective process constraints^[3]. A bidirectional constraint relationship is thus formed between data and mechanisms, which prevents model outputs from drifting toward purely statistical tendencies detached from actual processes and simultaneously improves their precision. This makes the model highly stable and verifiable in explaining pollution causes and evaluating governance effectiveness, providing a solid and reliable methodological foundation for the construction of a comprehensive evidence chain to support targeted policy-making.

4. Restructuring the Decision-Making Chain for Targeted Policy-making Based on Monitoring Network Optimization

4.1 Targeted Pollution Identification and the Logic of Zonal and Tiered Control

The transition of monitoring networks from single-function data acquisition systems to high-density, multi-dimensional information systems has brought about a fundamental structural transformation in the cognitive framework of air pollution identification. Traditional macro-level judgments derived from average concentrations or annual indicators have obvious limitations in addressing the high spatiotemporal heterogeneity of pollution, thus pollution identification is gradually shifting toward a targeted approach that emphasizes process characteristics, structural differences and temporal sensitivity.

The optimization of monitoring networks has enhanced the ability to capture detailed information on pollution fluctuations, enabling the stable presentation of pollution intensity, component structure and variation rhythms of different spatial units across multiple time periods. Pollution hotspots, vulnerable sensitive areas and key transmission channels, once obscured by statistical smoothing, now enter the governance perspective with clearly defined boundaries and distinct characteristics. Targeted identification is not simply focused on high-value observations, but conducts comprehensive judgments by integrating pollution source orientation, exposure risk distribution and environmental carrying capacity differences [4], thus realizing the objectification translation of pollution problems at the cognitive level.

The logic of zonal and tiered control developed on this basis emphasizes the integration of monitoring results into governance design, and implements differentiated management arrangements across regions according to pollution contribution structures and environmental function positioning. This ensures that control intensity, measure combinations and implementation rhythms exhibit clearly stratified structural characteristics. This logic drives governance practices from homogeneous policy application to precise resource allocation, enabling the informational value generated by monitoring networks to be fully released in both spatial organization and policy implementation dimensions, thus significantly enhancing the ability of governance systems to respond to complex pollution patterns.

4.2 Evidence-based Policy Logic and Traceable Decision-making Mechanisms

The effectiveness of targeted policy-making at the institutional level depends on whether governance decisions can transition from experiential judgment to evidence-based support. Monitoring network optimization provides a critical pivot in this transition by establishing a direct linkage between observed facts and policy choices, thus furnishing policy logic with a clear, stable and verifiable information foundation.

Evidence-based policy logic focuses on integrating pollution identification outcomes, causal analysis conclusions and control measure selection within a unified logical framework. This ensures that policy actions go beyond principle-oriented statements and form data chains with explicit causal orientation. Traceable decision-making mechanisms are developed on this basis, which systematically label key elements such as monitoring data sources, analytical method selection, model parameter settings and threshold determination criteria. This enables each policy decision to be traced back to specific informational nodes and analytical rationales.

During operation, this mechanism strengthens the structural coupling between monitoring networks and governance systems, ensuring that technical analytical outputs are continuously embedded into policy processes rather than remaining at the level of auxiliary reference. The integrated system of evidence-based logic and traceability not only significantly enhances decision

transparency and standardization, but also provides clear bases for responsibility delineation, performance evaluation and policy adjustment. This enables targeted policy-making to gradually transform into a replicable and expandable organizational capability, and promotes the transition of governance systems from unstructured states reliant on individual experience to rational operational forms supported by data and rules.

4.3 Quantitative Evaluation of Policy Effects and Closed-loop Correction Mechanisms

With the in-depth implementation of the targeted policy-making concept, policy effect evaluation has gradually moved beyond traditional post hoc descriptive summaries toward the systematic quantitative characterization of both governance processes and outcomes. Monitoring network optimization provides sustained, stable and structurally coherent informational support for this shift [5]. The quantitative evaluation of policy effects is no longer limited to short-term concentration changes or isolated improvement magnitudes, but encompasses comprehensive analyses of pollution structural adjustments, spatial gradient evolution and temporal characteristic changes. This enables governance impacts to be accurately identified across extended temporal scales and broader spatial ranges.

Closed-loop correction mechanisms are established on the basis of such evaluations, where assessment outcomes are reversely embedded into monitoring network configuration optimization, analytical model refinement and decision rule adjustment processes. This ensures that governance systems maintain dynamic corrective capacity during operation. Within this mechanism, monitoring, analysis, policy implementation and evaluation form an interlinked and mutually feedback cycle structure, enabling targeted policy-making to evolve from one-time decision actions into a continuous iterative institutional process.

This mechanism reinforces the foundational role of monitoring networks throughout the policy lifecycle, supporting the continuous optimization of governance practices through information feedback and rule revision. It also promotes the gradual transition of air pollution prevention and control from stage-based interventions to structurally stable, logically coherent and self-correcting systemic governance forms.

5. Conclusion

This study explores the intrinsic relationship between environmental monitoring network optimization and targeted policy-making in air pollution prevention and control, and constructs a systematic analytical framework encompassing theoretical cognition, evidence generation and decision-making operation. The core of monitoring network optimization lies not in the expansion of station numbers, but in the enhancement of information efficiency, whose value is reflected in the effective support for characterizing pollution heterogeneity, identifying process features and providing governance feedback.

Network structural optimization under multi-objective constraints provides a stable foundation for data quality governance, model coupling and uncertainty management. Data-model systems built around evidence chains realize the transformation of monitoring information into credible and traceable decision-making bases. Furthermore, the restructuring of decision-making chains under closed-loop mechanisms facilitates the transition of targeted policy-making from stage-based interventions to institutionalized operation.

Embedding the optimization of environmental monitoring networks into governance logic contributes to strengthening the scientific rigor, transparency and stability of air pollution prevention and control, and provides a sustainable and efficient support pathway for the long-term advancement of targeted policy-making in air pollution control.

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