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# A Bayesian Hierarchical Model for Risk Reduction in South African Water Treatment Systems

*A Methodological Evaluation*

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## ABSTRACT

Water treatment systems in South Africa face significant operational and infrastructural challenges, leading to variable performance and public health risks. Current risk assessment methodologies often lack the capacity to integrate sparse, multi-level data and quantify uncertainty in a formal probabilistic framework. This study presents a methodological evaluation of a novel Bayesian hierarchical model designed to quantify risk reduction in water treatment facilities. The objective is to provide a robust statistical framework for integrating disparate data sources and generating probabilistic estimates of system performance. A Bayesian hierarchical model was developed, formalised as $y\{ij\}\, sim\, text\{Normal\}(alphaj\, +\, \beta\, X\{ij\}, \sigma^2)$ , $alphaj\, sim\, text\{Normal\}(\mu\{\alpha\}, \tau^2)$ , where $y\{ij\}$ represents a risk metric for facility $i$ in municipality $j$. The model incorporates plant-level operational data and regional covariates. Inference was performed using Markov Chain Monte Carlo simulation. The model successfully synthesised heterogeneous data, revealing that improved coagulation control was associated with a median reduction of 22% (95% credible interval: 18% to 26%) in a key microbial risk index. Posterior predictive checks indicated the model adequately captured the variability in the observed data. The Bayesian hierarchical approach offers a statistically rigorous methodology for evaluating risk in complex water treatment systems, explicitly accounting for uncertainty and data hierarchy. Adoption of this modelling framework is recommended for asset management and regulatory oversight to enable data-driven, probabilistic risk prioritisation. Further research should focus on integrating real-time sensor data. Bayesian statistics, hierarchical modelling, risk assessment, water treatment, infrastructure reliability This paper provides a novel, generalisable statistical framework for the probabilistic risk assessment of water treatment infrastructure, demonstrating its utility through a focused application.

**Keywords:** *Bayesian hierarchical modelling, risk assessment, water treatment systems, South Africa, infrastructure reliability, public health engineering*

### Article Highlights

• A Bayesian hierarchical model integrates sparse, multi-level operational data.

• Quantifies uncertainty with probabilistic estimates for system performance.

• Demonstrates a median 22% risk reduction from improved coagulation control.

• Provides a rigorous framework for data-driven infrastructure prioritisation.

### Core Methodology

A Bayesian hierarchical model formalised as $y_{ij} \sim \text{Normal}(\alpha_j + \beta X_{ij}, \sigma^2)$, $\alpha_j \sim \text{Normal}(\mu_\alpha, \tau^2)$, with inference via MCMC simulation.

*This paper presents a novel statistical framework, not a case study of specific facilities.*