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Bayesian Hierarchical Modelling for Reliability Diagnostics in Nigerian Water Treatment Systems

A Case Study (2000–2026)

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ABSTRACT

Background: The reliability of water treatment infrastructure in many regions is compromised by ageing assets, inconsistent maintenance, and sparse performance data. Conventional reliability assessments often fail to adequately quantify uncertainty and integrate multi-level operational data, leading to suboptimal maintenance strategies and resource allocation.

Purpose and objectives: This case study aims to develop and evaluate a Bayesian hierarchical modelling framework for the reliability diagnostics of water treatment systems. The objective is to provide a robust probabilistic tool for identifying critical failure modes and informing targeted maintenance interventions.

Keywords: *Bayesian hierarchical modelling, Reliability engineering, Water treatment systems, Sub-Saharan Africa, Infrastructure diagnostics, Failure mode analysis, Maintenance optimisation*

Article Highlights

- Chemical dosing systems identified as the least reliable subsystem with high posterior probability.
- Significant plant-to-plant variability captured via hierarchical random effects.
- Framework quantifies uncertainty, moving beyond deterministic failure analysis.
- Provides a probabilistic basis for targeting maintenance resources.

Core Statistical Model

Bayesian hierarchical Weibull regression: $T_{ij} \sim \text{Weibull}(\alpha, \lambda_{ij})$, $\log(\lambda_{ij}) = \beta_0 + \beta_1 X_{1ij} + u_j$, with $u_j \sim N(0, \sigma^2_u)$ capturing plant-specific random effects.

This study presents a probabilistic framework for infrastructure diagnostics in data-sparse environments.