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The Impact of Spatial Connectivity Structures on Model Fit, Inference, and Data Integration in Spatial Epidemiology and Wastewater-Based Epidemiology: A Systematic Review

Background: Spatial connectivity structures, how geographic units are defined as neighbors via contiguity, distance, k-nearest neighbors, or network-informed weights, are foundational to classical spatial models (SAR, GWR, CAR/BYM). Evidence across spatial epidemiology, public health, and wastewater-based epidemiology (WBE) demonstrates that connectivity choices materially influence model fit, parameter estimation, and epidemiological inference. This is particularly consequential when integrating incomplete, misaligned, or disjoint data from clinical, survey, and wastewater sources.

Methods: We synthesized evidence from peer-reviewed literature (2000–2026) applying CAR/BYM, SAR, GWR, and SPDE-based models in spatial epidemiology and WBE. We extracted findings on: (i) connectivity structure types and their effects on model fit (DIC, WAIC, AIC, RMSE); (ii) influence on parameter estimation and inference (coefficients, standard errors, spatial effects); (iii) handling of misaligned data (e.g., hospital-wastewater catchment misalignment); and (iv) the role of behaviour-informed connectivity from survey data.

Preliminary Key Findings: Connectivity choice affects model fit: Across multiple studies, DIC and WAIC consistently favor spatial models with structured random effects over non-spatial alternatives. Changing the connectivity structure (e.g., from contiguity to distance-based or mobility-informed weights) alters AIC by meaningful margins, with BYM/BYM2 and Leroux CAR often outperforming intrinsic CAR depending on data characteristics (MacNab, 2022; Ugarte et al., 2014; Adin et al., 2019). SPDE-based and Leroux priors show dataset-dependent improvements in fit and predictive performance (Lü et al., 2023; Sianga et al., 2024; Jaya & Folmer, 2021).

Parameter estimation and inference are sensitive to connectivity: The chosen neighborhood graph governs smoothing, identifiability of spatial effects, and precision of estimates for reproduction number (Rt) and case ascertainment rate (CAR) (Watson et al., 2023, 2024). Misspecified connectivity can bias parameter estimates and alter significance of covariate effects (Kubara & Kopczewska, 2024; Berry et al., 2008; Amdaoud et al., 2021). Spatial models that incorporate structured random effects improve uncertainty quantification and inference stability (Asmarian et al., 2019; Blangiardo et al., 2013; Osei et al., 2019).

Misaligned and disjoint data require connectivity-aware methods: Hospital-wastewater catchment misalignment is a concrete challenge where sewer-network-defined catchments rarely align with health jurisdiction boundaries. Connectivity structures that reflect sewer topology and population mobility improve integration of clinical and wastewater data (Sharara et al., 2021; Hassard et al., 2023; Bicker et al., 2025). GIS-based catchment delineation and coupled epidemiological-hydraulic models provide principled approaches to reconcile misalignment (Domokos et al., 2022; Yeager et al., 2021).

Behaviour-informed connectivity outperforms geographic structures: Survey-derived mobility, social contact, and healthcare-seeking data enable connectivity structures (gravity models, network-based weights) that capture non-local transmission pathways. Evidence shows behaviour-informed connectivity often outperforms purely geographic structures when mobility drives spread (Cuadros et al., 2022; Venkatramanan et al., 2021; Buckee et al., 2021). However, benefits depend on data quality, pathogen dynamics, and temporal alignment (Patil et al., 2021).

Similarities and differences between PH/E and WBE: Both domains show high sensitivity to connectivity choice and benefit from structured spatial random effects. WBE studies more frequently use network-informed weights reflecting sewer topology (44% vs. 18% in PH/E), while PH/E studies more frequently use distance-based structures (56% vs. 32% in WBE). WBE faces unique misalignment challenges (sewershed vs. administrative boundaries) that PH/E studies encounter less frequently.

Guidance for connectivity selection: A structured workflow is recommended: (i) define candidate connectivity families (contiguity, distance, k-NN, behaviour-informed); (ii) compare using DIC/WAIC/AIC and cross-validated predictive metrics; (iii) assess parameter stability across specifications; (iv) conduct sensitivity analyses; (v) select structure balancing fit, stability, and interpretability (Kanankege et al., 2020; Louzada et al., 2021; Nazia et al., 2022; Casey et al., 2017).

Conclusions: Spatial connectivity structure choice is not neutral. It substantially affects model fit, parameter estimates, and inference, particularly with incomplete, misaligned, or disjoint data. We provide evidence-based guidance for connectivity selection in spatial epidemiology and WBE, emphasizing routine sensitivity analyses, behaviour-informed structures when mobility data are available, and explicit handling of hospital-wastewater catchment misalignment.
Keywords: Spatial connectivity structures; spatial weights matrix; CAR/BYM; spatial epidemiology; wastewater-based epidemiology; misaligned data; model fit; inference; behaviour-informed connectivity.

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