SPATIAL DEPENDENCE OF RESERVOIR TROPHIC STATES IN THE JAGUARIBE RIVER BASIN

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INTRODUCTION

Eutrophication is a major environmental challenge in lakes and reservoirs, especially in semi-arid regions where water scarcity already limits multiple uses of water resources. In Ceará, northeastern Brazil, this issue is particularly relevant because, according to recent COGERH (2026) reports, a large fraction (78%) of reservoirs exhibits eutrophic or hypereutrophic conditions, limiting human consumption, industrial use and increasing water treatment cost. The Jaguaribe River basin is a central component of the state's water system and is characterized by a dense network of reservoirs that operate in a strongly interconnected hydrological setting rather than as isolated units.

In this context, trophic states may show joint behavior across reservoirs due to longitudinal flow regulation, operational transfers, and spatial connectivity. However, trophic state observations are ordinal categories derived from the Trophic State Index, which introduces ties and makes classical continuous dependence methods less appropriate. To address this, we use a latent-variable copula framework that reconstructs continuous latent realizations compatible with the observed ordinal structure, allowing flexible modeling of non-linear dependence.

The aim of this study is to investigate the spatial dependence structure of trophic states in reservoirs of the Jaguaribe River basin, with emphasis on the main hydrological axis and the role of auxiliary tributary reservoirs. We assess pairwise dependence using bivariate copulas and extend the analysis to a multivariate C-vine copula model. The central question is whether trophic conditions propagate through the basin in a way that can be captured by probabilistic dependence models.

METHODOLOGY

The study area is situated in the Jaguaribe River basin, which covers more than half of the territory of Ceará and lies within the Brazilian semi-arid region. The analysis focused on six reservoirs: Orós, Castanhão, and Arneiroz II on the main hydrological axis; and Canoas, Muquém, and Rivaldo de Carvalho as tributary reservoirs. Orós occupies an intermediate position in the main system, while Castanhão is the largest reservoir in the basin and plays a central operational role. These smaller tributary reservoirs perennialize river stretches and share basin water demands, according to ANA (2017). To evaluate the spatial dependence structure, specific reservoir pairs were defined to compare the association along the main river channel with the dynamics of these tributary systems. Orós was established as the central reference point for these auxiliary pairs because, as the

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first major main-stem reservoir upstream, it directly receives the regulated inflows from all three tributaries.

Quarterly trophic-state observations from May 2008 to November 2025 were obtained from the Ceará Hydrological Portal, with hydrological data provided by COGERH. The response variable is ordinal with four categories defined according to adaptations of the Trophic State Index (Lamparelli, 2004): oligotrophic, mesotrophic, eutrophic, and hypereutrophic. Since some quarterly observations were unavailable due to suspended sampling caused by intense macrophyte coverage, reservoir drying, or operational issues, only concurrent observations were retained for each reservoir pair, resulting in pair-specific effective sample sizes, as shown in Table 1.

Table 1 - Sample size of concurrent water quality observations for the selected reservoir pairs from 2008 to 2025

Reservoir pair	Orós–Castanhão	Orós–Arneiroz II	Orós–Canoas	Orós–Riv. de Carvalho	Orós–Muquém
Sample size	62	64	61	59	49

Since the observed trophic states are ordinal, a latent-variable approach was adopted (Agresti, 2010). Each observed category was linked to an unobserved continuous variable through threshold intervals. Continuous latent values were generated within the category-specific intervals using a Gaussian latent distribution. This procedure preserves the ordinal structure while reducing the impact of ties and producing pseudo-continuous data suitable for copula modeling. To account for uncertainty introduced by the latent reconstruction, 1,000 latent datasets were randomly generated. Copula parameters, dependence measures, and model selection criteria were estimated for each dataset, and the corresponding average values were used for model comparison and copula selection.

For the bivariate analysis, eight copula families were evaluated: Frank, Ali-Mikhail-Haq, Gumbel, Joe, Clayton, Gaussian, Survival Clayton, and Survival Gumbel (Nelsen, 2006). Parameters were estimated by maximum pseudo-likelihood. Model choice was based on the average AIC, BIC, and RMSE between empirical and theoretical copulas across the latent reconstructions. Dependence was modeled through copula functions (Sklar, 1959). Kendall's tau and Spearman's rho were used as descriptive association measures and to compare the dependence implied by the fitted copulas with that obtained from the latent reconstructions.

After selecting the best-fitting copula for each reservoir pair, a second Monte Carlo procedure was conducted to simulate joint and conditional trophic-state probabilities. For each of 10,000 latent realizations, 50,000 observations were simulated from the selected copula and subsequently reclassified into the original trophic categories using empirical thresholds. The resulting simulated frequencies were then aggregated to estimate model-based joint and conditional probabilities.

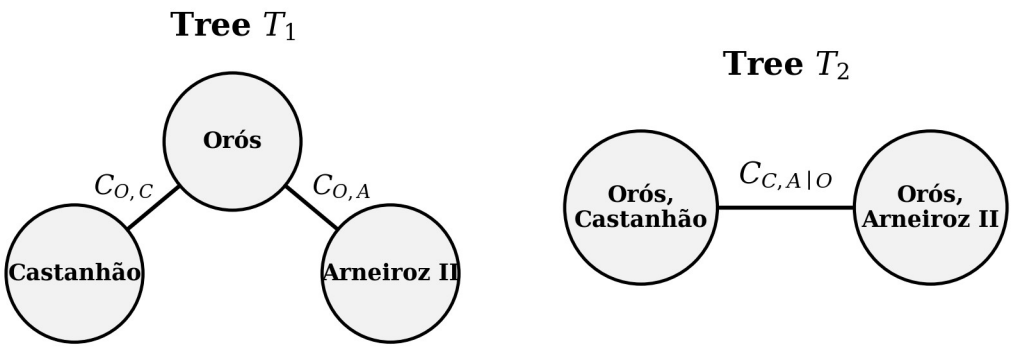


Figure 1. Schematic representation of the C-vine copula decomposition structure for the primary reservoir system.

To extend the analysis to a multivariate framework, a three-dimensional C-vine copula (Czado & Nagler, 2022) was fitted to the main-axis reservoirs, with Orós assigned as the root node (Figure 1). This choice reflects both its intermediate hydrological position between Arneiroz II and Castanhão along the main channel and its stronger pairwise dependence with the other main axis reservoirs, making it the most suitable center for the hierarchical vine structure. The first tree modeled the unconditional dependence between Orós and the other two main-axis reservoirs, while the second tree captured the conditional dependence between Castanhão and Arneiroz II given Orós.

RESULTS

The main-axis reservoir pairs exhibited the strongest dependence patterns in the study. For Orós–Castanhão, simultaneous eutrophic conditions were frequent, and the two reservoirs shared the same trophic state in a substantial proportion of observations. For Orós–Arneiroz II, dependence was also present, but the association was weaker and less concentrated in the same joint categories, reflecting the larger hydrological distance and the regulatory role of the basin structure.

Among the fitted copulas, the AMH copula provided the best overall fit for Orós–Castanhão, while the Gaussian copula was selected for Orós–Arneiroz II. Although the latent reconstruction produced lower dependence estimates than the raw observed categories, the fitted copula models accurately reproduced the latent dependence structure.

The simulated joint distributions indicated that the main-axis system is dominated by eutrophic co-occurrence. For Orós–Castanhão, approximately half (50.3%) of the joint probability mass was concentrated in the eutrophic–eutrophic configuration, while simultaneous hypereutrophic events were rare. A similar but slightly weaker pattern was observed for Orós–Arneiroz II, where eutrophic co-occurrence remained important and extreme joint degradation occurred with low probability.

Conditional simulated probabilities were not identical when reversing the conditioning reservoir. When Orós reached eutrophic or worse conditions, Castanhão usually remained in a degraded trophic state as well, suggesting stronger association along the main axis. For Arneiroz II, the dependence was weaker, but still consistent with the idea that the main river network conveys trophic conditions downstream.

In contrast, pairs involving tributary reservoirs exhibited weak dependence, with dependence coefficients generally close to zero. Orós–Canoas, Orós–Rivaldo de Carvalho, and Orós–Muquém showed small dependence coefficients. For Orós–Canoas and Orós–Rivaldo de Carvalho, the eutrophic–eutrophic configuration remained the most frequent state, although with substantially weaker dependence than that observed along the main axis. In contrast, Orós–Muquém displayed a distinct pattern characterized by a predominance of discordant trophic states. To capture these weak structures, the Frank copula provided the best fit for all three pairs. Joint hypereutrophic events were rare across all pairs formed between Orós and tributary reservoirs, and the simulations suggested limited propagation of severe degradation from these tributary reservoirs to Orós.

The multivariate C-vine analysis supported the main findings from the pairwise models. After conditioning on Orós, a residual positive dependence remained between Castanhão and Arneiroz II, showing that Orós explains part, but not all, of the dependence along the main axis. The Gaussian conditional copula was the most suitable model for this second tree. Joint simulations from the full vine model showed that the most probable multivariate state was the simultaneous eutrophic configuration of all three main-axis reservoirs. Furthermore, conditional simulations revealed a high probability (88.3%) of all main axis reservoirs being in eutrophic or worse conditions when Castanhão was degraded, contrasting with 76.7% and 61.2% when conditioning on Orós and

Arneiroz II, respectively. This reflects the downstream integrative role of Castanhão, where elevated trophic conditions signal widespread axis-scale degradation. In contrast, for the hypereutrophic class, conditional probabilities remained low (0.8% to 8.6%), reinforcing the rarity of synchronized extreme events.

In the context of water resources and drought management, these findings are particularly relevant during prolonged drought events, which frequently affect the state of Ceará. During periods of reduced reservoir storage and longer water residence times, water-quality conditions may deteriorate and contribute to increasing management challenges. Incorporating spatial dependence structures into drought contingency planning may help complement existing water allocation strategies by providing information on the potential for synchronized trophic-state deterioration along the main hydrological axis. This perspective may support more integrated monitoring and management actions aimed at maintaining water quality and water security during periods of climatic stress.

CONCLUSIONS

The latent-variable copula approach provided a practical way to analyze dependence among ordinal trophic-state classifications. Results demonstrated stronger dependence along the main Jaguaribe axis, particularly between Orós and Castanhão, whereas pairs involving tributary reservoirs exhibited substantially weaker association. The dominant joint behavior corresponds to eutrophic conditions, while simultaneous hypereutrophic events are uncommon. Furthermore, multivariate analysis revealed that Orós does not fully explain the dependence between Castanhão and Arneiroz II, indicating residual basin-scale connectivity. Methodologically, the proposed approach was adequate for this application. From a management perspective, these findings support integrated water-quality monitoring along the main axis and suggest that Castanhão serves as a strategic indicator of broader trophic conditions throughout the basin.

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