Scaling of Hyporheic Metabolism Across Ecoregions in the Columbia River Basin

1. **Introduction**

The hyporheic zone, where surface water and groundwater interact, is a dynamic and vital component of riverine ecosystems, crucial for nutrient cycling and organic matter transformation (Boano et al., 2014; Cardenas, 2008). This zone supports microbial processes that transform and cycle carbon and nutrients, significantly influencing localized hyporheic processes such as nutrient retention, denitrification, and carbon fluxes (Boano et al., 2014; Grant et al., 2018). The high heterogeneity in hyporheic processes, generated by interactions across a wide range of scales, poses a significant challenge for understanding these functions (Stonedahl et al., 2010; Lee et al., 2020).

Addressing this complexity requires examining the self-similarity of underlying mechanisms expressed through different processes across scales. Self-similarity, linked to fractal and potentially multifractal structures, provides a framework for understanding how various processes at one scale can have analogous counterparts at other scales (Wörman et al., 2007; Boano et al., 2014). For instance, the mechanisms driving regional flow systems, subsurface flow, and baseflow contribution at larger scales can be seen as analogous to local processes like bedform geometry influencing hyporheic exchange (Lee et al., 2020; Cardenas, 2008).

Topography fundamentally controls the distribution and complexity of flow paths within the hyporheic zone, influencing the range of residence times for water and solutes (Boano et al., 2009; Cardenas, 2008). These flow paths, from short and direct to long and meandering, create diverse residence times that follow power-law distributions, where a significant proportion of water experiences extended transit times due to intricate topographic features (Wörman et al., 2007; Stonedahl et al., 2010; Grant et al., 2018). This hierarchical structure, from large-scale landscape features to fine-scale sediment arrangements, reflects the fractal nature of localized hyporheic processes, which can influence broader cumulative hyporheic functions such as nutrient cycling and carbon sequestration (Grant et al., 2018; Lee et al., 2020; Boano et al., 2014; Chen et al., 2024).

Understanding the self-similarity of mechanisms across different spatial scales can help elucidate how cumulative hyporheic function scales from reaches to ecoregions. At the reach scale, local bedform features such as ripples and dunes create zones of water infiltration and exfiltration, establishing complex flow paths (Cardenas, 2008; Wörman et al., 2007). At the stream level, features such as pools, riffles, and channel bends generate similar patterns of upwelling and downwelling, maintaining the self-similar nature of hyporheic exchange (Boano et al., 2014). At the basin and regional scales, larger geomorphological features like river bars, islands, and alluvial fans drive significant hyporheic exchange, mirroring patterns observed at smaller scales but on a broader spatial canvas (Chen et al., 2024).

To capture the complexity and potential multifractal nature of these processes, we propose examining cumulative hyporheic function. These cumulative functions provide a more integrated view of hyporheic processes across scales, allowing us to explore variations in scaling exponents and detect multifractal behavior. This approach shifts the focus from direct indicators of hyporheic exchange to cumulative measures that reflect the self-similar mechanisms driving biogeochemical processes across different spatial extents.

In this study, we aim to explore scaling relationships based on cumulative hyporheic function to provide an across-scale understanding of biogeochemical functions from reaches to ecoregions within the Columbia River Basin. By examining how these cumulative functions scale and identifying variations in scaling exponents, we seek to detect potential multifractal behavior in hyporheic processes. This approach will enhance our ability to predict and manage the ecological functions of riverine systems across diverse spatial contexts (Wollheim et al., 2022).