Coupling Hydrological and Economic Leakages to Share Nitrogen pollution Responsibility among Cities in Pearl River Basin

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Nitrogen pollution in river systems represents a critical environmental challenge that increasingly leads to estuarine eutrophication and coastal hypoxia worldwide. Anthropogenic activities release substantial nitrogen in upstream areas and effective riverine pollution management fundamentally requires fair responsibility sharing across regions. Existing territorial and hydro-centric strategies fail to account for the hidden economic links between upstream production and downstream consumption. Addressing this critical disciplinary gap this study investigates how interregional macroeconomic trade and final consumption demand drive transboundary nitrogen pollution across different sectors and how hydrological transport amplifies the spatial inequality between economic beneficiaries and environmental receivers in a major river basin. To answer these questions, we develop a coupled hydro-economic framework that bridges hydrological routing with multisectoral supply chains. This integrated methodology combines a Multi-Regional Input Output (MRIO) model with the process-based Soil and Water Assessment Tool (SWAT). The empirical application encompasses 46 cities within the Pearl River Basin in China. We construct a topology based recursive propagation algorithm to accurately quantify pollutant transport and attenuation along the entire river to ocean continuum. We utilize comprehensive datasets including SWAT simulated hydrological and nutrient fluxes calibrated with recent streamflow data alongside highly resolved land use records. These physical measurements are tightly coupled with sectoral discharge inventories spanning 42 economic sectors and regional input output tables for 313 cities. This deep integration enables us to seamlessly trace transboundary nitrogen flows from their initial terrestrial discharge sources through the complex river network to the coastal ocean and precisely attribute these final loads to their ultimate macroeconomic consumption endpoints. By tightly coupling these two dimensions our approach explicitly links economic drivers with hydrological consequences to reveal the severe spatial mismatch between economic value accumulation and environmental burden retention. This provides a quantitative basis for shifting governance toward a beneficiary pays principle. Our results of source attribution show that under a strict hydrological perspective upstream regions appear as the primary pollution sources contributing 68 percent of the estuarine nitrogen load. Yet from a consumption perspective upstream responsibility is halved to 38 percent while the responsibility of the affluent Greater Bay Area core cities triples to 15 percent. Furthermore, demand from outside the basin drives 34 percent of the total estuarine load heavily induced by external construction and light manufacturing sectors that rely on upstream agricultural outputs. The results also uncover a profound spatial mismatch between economic benefits and environmental costs. The spatial Gini coefficient for production driven discharge responsibility stands at 0.72 indicating high inequality in pollution generation. The unidirectional hydrological transport along the West River further amplifies this inequality by concentrating the involuntary environmental burden downstream. This hydrological routing raises the cumulative external consequence Gini coefficient to an extreme 0.89. By integrating the economic allocation of trade benefits with the spatial distribution of hydrological burdens, we classify the regional cities into four distinct structural roles. Exploitative Free Riders such as Guangzhou and Shenzhen strategically outsource pollution intensive production while geographically evading hydrological pollution accumulation. Sacrificial Receivers such as Zhaoqing and Wuzhou bear involuntary hydrologic burdens without reaping the associated economic rewards. Self-inflicted Stressors, such as Nanning and Liuzhou, act as the internal engine of the basin generating 69 percent of the localized discharge but remaining structurally trapped in high pollution agricultural loops. Insulated Bystanders play a marginal role in the basin network. Ultimately the upstream regions function as a resource frontier

that exports economic value to national markets while retaining the environmental burden locally and transmitting it downstream through the river network. These findings deliver crucial evidence for designing equitable transboundary watershed management policies tailored to specific city functions.