

Project title: Tracer-Aided Water Quality Modelling at Continental Scale in Europe

Project leader: Dr. Songjun Wu from Leibniz-Institut für Gewässerökologie und Binnenfischerei (IGB)

Email: songjun.wu@igb-berlin.de

Abstract

Anthropogenic activities, particularly intensive agriculture, have doubled biologically available nitrogen (N) inputs to the terrestrial biosphere since pre-industrial times (Galloway et al., 2008). This surge has driven a sixfold increase in global riverine fluxes of dissolved inorganic nitrogen, whose excess has become a primary source of eutrophication in rivers, estuaries, and coastal seas worldwide (Green et al., 2004). Europe is an example of this long-term shift where average N surplus reached 60 kg/ha·yr in agricultural catchments, leading to high N levels in rivers despite decades of policy efforts under the EU Water Framework Directive (European Environment Agency, 2018). These challenges underscore the necessity to further advance the understanding on N cycling at the continental-scale.

Spatial distributed water quality modelling offers an effective means to formalize such knowledge, which has been increasingly developed and applied at plot- to catchment-scales (e.g., HYPE Lindström et al., 2010, SWAT, Rathjens et al., 2015, and mHM-nitrate, Yang et al., 2018). However as reviewed in Wellen et al., (2015), over 80% of the applications rely on streamflow and in-stream concentrations at a single location (mostly at outlet). This poses a potential risk of “equifinality” (Beven & Smith, 2015), a phenomenon of inaccurate process representations yielding deceptively good results through error compensation, thus leading to overconfidence in a model's ability to reproduce within-basin dynamics (Wellen et al., 2015).

The inclusion of stable water isotopes can mitigate such uncertainties. As conservative tracers, ^2H and ^{18}O are independent of biogeochemical reactions and naturally integrate field heterogeneity, thus providing effective constraints on spatial distributed (dis)connections of hydrological flow paths (Kuppel et al., 2018; Tetzlaff et al., 2015). Many studies have demonstrated the benefits of using tracers in hydrological modelling, but this has been rarely integrated to water quality modelling. It thus remains unclear regarding *whether and how stable water isotopes can strengthen the simulation and process inference of water quality models*.

To address these knowledge gaps, we have recently developed and applied three tracer-aided hydrological and water quality models across multiple spatial scales, including EcoPlot (Landgraf et al., 2022), a 1D hydrological model for plot-scale ecohydrological modelling; Ech_2O -iso-nitrate (Yang et al., 2023), a spatially-distributed physics-based model for catchment-scale nutrient cycling; and EcoTWIN (Wu et al., 2025), a spatially-distributed process-based model for continental-scale water and nitrogen dynamics. Together, these models provide a unified framework for systematically investigating the mechanisms governing coupled water and nutrient cycles from plot to continental scales.

Leveraging the parallel computing capability of the DKRZ cluster, we plan to calibrate these models across major river basins in Europe using available observations of discharge, in-stream isotope compositions, and nitrate concentrations. By incorporating tracer simulations, the models can not

only reproduce the celerity response at catchment outlets but also simulate hydrological transport, mixing, and biogeochemical transformations along flow paths. In this regard, the tracer-aided modelling framework may show a strong potential to evolve into a digital twin of water and nitrogen cycling across Europe, providing a powerful tool for risk assessment and the integrated management of water quantity and quality.

References

- Beven, K., & Smith, P. (2015). Concepts of Information Content and Likelihood in Parameter Calibration for Hydrological Simulation Models. *Journal of Hydrologic Engineering*, *20*, 6916. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0000991](https://doi.org/10.1061/(ASCE)HE.1943-5584.0000991)
- European Environment Agency. (2018). *European Waters-Assessment of Status and Pressures*. Publications Office of the European Union, Luxembourg. Retrieved from <https://www.eea.europa.eu/publications/state-of-water>
- Galloway, J., Townsend, A., Erismann, J. W., Bekunda, M., Cai, Z., Freney, J., et al. (2008). Transformation of the Nitrogen Cycle: Recent Trends, Questions, and Potential Solutions. *Science (New York, N.Y.)*, *320*, 889–92. <https://doi.org/10.1126/science.1136674>
- Green, P., Vörösmarty, C., Meybeck, M., Galloway, J., Peterson, B., & Boyer, E. (2004). Pre-Industrial and Contemporary Fluxes of Nitrogen Through Rivers: A Global Assessment Based on Typology. *Biogeochemistry*, *68*, 71–105. <https://doi.org/10.1023/B:BIOG.0000025742.82155.92>
- Kuppel, S., Tetzlaff, D., Maneta, M., & Soulsby, C. (2018). ECH2O-iso 1.0: Water isotopes and age tracking in a process-based, distributed ecohydrological model. *Geoscientific Model Development*, *11*, 3045–3069. <https://doi.org/10.5194/gmd-11-3045-2018>
- Landgraf, J., Tetzlaff, D., Wu, S., Freymüller, J., & Soulsby, C. (2022). Using stable water isotopes to understand ecohydrological partitioning under contrasting land uses in a drought-sensitive rural, lowland catchment. *Hydrological Processes*, *36*(12). <https://doi.org/10.1002/HYP.14779>
- Lindström, G., Pers, C., Rosberg, J., Strömqvist, J., & Arheimer, B. (2010). Development and test of the HYPE (Hydrological Predictions for the Environment) model – A water quality model for different spatial scales. *Hydrology Research*, *41*. <https://doi.org/10.2166/nh.2010.007>
- Rathjens, H., Oppelt, N., Bosch, D., Arnold, J., & Volk, M. (2015). Development of a grid-based version of the SWAT landscape model. *Hydrological Processes*, *29*, 900–914. <https://doi.org/10.1002/hyp.10197>
- Tetzlaff, D., Buttle, J., Carey, S. K., Mcguire, K., Laudon, H., & Soulsby, C. (2015). Tracer-based assessment of flow paths, storage and runoff generation in northern catchments: A review. *Hydrological Processes*, *29*(16), 3475–3490. <https://doi.org/10.1002/HYP.10412>
- Wellen, C., Kamran-Disfani, A.-R., & Arhonditsis, G. (2015). Evaluation of the Current State of Distributed Watershed Nutrient Water Quality Modeling. *Environmental Science & Technology*, *49*. <https://doi.org/10.1021/es5049557>
- Wu, S., Tetzlaff, D., Zheng, Y., & Soulsby, C. (2025). *EcoTWIN 1.0: A Fully Distributed Tracer-Aided Ecohydrological Model Tracking Water, Isotopes, and Nutrients*. <https://doi.org/10.5194/egusphere-2025-3941>
- Yang, X., Jomaa, S., Zink, M., Fleckenstein, J., Borchardt, D., & Rode, M. (2018). A New Fully Distributed Model of Nitrate Transport and Removal at Catchment Scale. *Water Resources Research*, *54*. <https://doi.org/10.1029/2017WR022380>
- Yang, X., Zhang, X., Graeber, D., Hensley, R., Jarvie, H., Lorke, A., et al. (2023). Large-stream nitrate retention patterns shift during droughts: Seasonal to sub-daily insights from high-frequency data-model fusion. *Water Research*, *243*, 120347. <https://doi.org/10.1016/j.watres.2023.120347>