



## Capturing Water Scarcity and Abundance under Change: A Multi-Sector Hydro-Economic Scenario Ensemble Approach for Thuringia

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Anticipating future water security is essential for sustainable development, food security, and economic stability across regions and sectors. Water scarcity and abundance are increasingly shaped by the combined effects of socio-economic development and climate change, yet their spatial patterns under deep uncertainty have not yet been systematically explored, particularly for regions such as Thuringia in Germany, which has historically been considered water abundant. Previous studies have typically assessed water scarcity using single-sector models or limited scenario frameworks, neglecting sectoral and regionally specific patterns of change. This limits our ability to identify regions that may remain water abundant despite profound change.

This study examines where and to what extent water scarcity and abundance emerge under combined socio-economic and climatic change, and how robust these outcomes are under deep uncertainty. We show that explicitly representing interacting water users within a multi-agent hydro-economic framework fundamentally alters the projected spatial distribution of future water stress and surplus.

Using a high-resolution multi-agent system (MAS) that integrates industrial, household, and agricultural water demands within a large-scale model of Thuringia, we construct an ensemble of water-use trajectories coupled with soil moisture projections from mHM as well as groundwater and surface water projections. These trajectories combine policy adjustments with regionalized SSP-RCP scenarios of population development, GDP, agricultural prices, and climate impacts. We employ econometric water demand functions for industrial water use across 19 districts and household demand across 800 water supply areas. Agricultural water use is represented through the coupled hydro-economic model DroughtMAS, comprising more than 1000 representative agricultural agents calibrated via Econometric Mathematical Programming (EMP) and driven by projected yield anomalies under droughts and hydro-climatic extremes, which are derived from a LASSO-regression-parametrized yield model.

Our results reveal that despite overall declining water use, localized changes—such as urban growth, increasing irrigation demand, and regional declines in water availability—can intensify potential water scarcity. In a broader context, these findings demonstrate that future water risk is not solely climate-driven but driven by a combination of socio-economic development pathways and policy choices. Accounting for these dynamics is therefore critical for identifying resilient

regions and developing robust water governance under uncertainty, and provides a framework to explicitly quantify water abundance alongside scarcity within a coupled socio-economic and hydro-climatic system.