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Exploring Global and Local Water Scarcity Dynamics through Causal Discovery and Structural Causal Models

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Water scarcity is driven by diverse natural and anthropogenic factors and represents a critical global challenge. Structural Causal Models are powerful tools to reveal the intricate interactions among social, ecological and hydrological components within human-water systems affected by water scarcity. This study integrates causal thinking into statistical and data-driven hydrological modelling, offering a different perspective on understanding system dynamics affecting water resources in water-scarce regions, the so-called water scarcity hotspots.

In this work we apply causal discovery methods to independent timeseries of sectoral water demand, social-economic variables, meteorological drivers and groundwater depletion to obtain a causal network representing human-water system interactions at global water scarcity hotpots. To derive this network we use global datasets and advanced causal network learning algorithms, specifically (Joint-)PCMCI (Runge et al., 2023). Recognizing the importance of large data sample sizes for a robust global causal network, we further extend our approach to construct a causal network specific to one of the water scarcity hotspots (California), using more detailed local data. Therefore, our framework provides a comprehensive understanding of water scarcity dynamics including both global and local scales. Through a comparative analysis of network outcomes derived from global datasets with those specific to California, we evaluate the effectiveness of our causal inference modelling framework.

After conducting and evaluating the causal networks at global and local scale, we applied methods from structural causal modelling and statistical machine learning to estimate causal effects of anthropogenic or natural system changes on water availability at water scarcity hotspots. This framework allows us to answer important (counterfactual) questions, such as understanding how the rate of unsustainable groundwater abstraction is affected by shifts in water management practices e.g., a reduction in irrigated cropland area.

As such, this work contributes to understanding how using causal inference methods are valuable to modelling of water scarcity, ultimately providing input to informed decision-making in water resource management and finding strategies to mitigate water scarcity impacts.

Runge, J., Gerhardus, A., Varando, G., Eyring, V., & Camps-Valls, G. (2023). Causal inference for time series. *Nature Reviews Earth & Environment*, *4*(7), 487-505.