

# Title:

## *Unveiling Invisible Water Flows in Socio-Hydrological Systems*

### **Dissertation Summary**

Ubuntu is an ancient African word that emphasizes the interconnectivity of individuals with their surrounding societal and physical worlds. This thesis is grounded in this interconnectivity and investigates global water teleconnections within socio-hydrological systems, focusing on virtual water trade and atmospheric moisture connections. Today, scientific and ethical questions in hydrology demand an understanding of the globality of the water cycle, where hydrological flows interact across different scales with globalizing *stimuli* (e.g., climate dynamics or food demand) that have repercussions on local water management. Effective action based on this understanding necessitates deepening our knowledge of global water interconnections, particularly through virtual and atmospheric moisture flows that link distant regions of the planet.

Atmospheric moisture flows and virtual water flows are both bilateral systems that connect source (export) and sink (import) and both depend on soil moisture content and evapotranspiration dynamics, albeit at different spatial and temporal scales. Virtual water trade reflects the socio-economic drivers shaping global water redistribution, whereas atmospheric moisture flows are governed by geophysical factors, including climatology, orography, meteorology, and vegetation, which influence water vapor transport from its origin to precipitation destinations.

In the virtual water trade literature, socio-economic drivers have been extensively explored at the country level. However, analyses at the corporate scale remain largely overlooked, despite transnational corporations (TNCs) being the dominant forces shaping the global food system today. In particular, TNCs engaged in the trade of crucial grains play a pivotal role in the global food market, yet their influence on global virtual water trade dynamics remains insufficiently explored. This thesis addresses key research questions in this direction, offering a novel perspective on the virtual water footprint of TNCs at the sub-national scale of production. Through emblematic case studies in tropical and subtropical regions, it provides practical tools to enhance our understanding of how TNCs shape water teleconnections at both local and global scales. This perspective underscores the importance of high spatial granularity in estimating virtual water flows, as finer-scale assessments are crucial for capturing the localized pressures of global socio-economic dynamics.

The tropical and subtropical regions assessed are not only central to global food production—representing the world's most critical breadbaskets—but also play a fundamental role in maintaining regional and global hydrological stability through land-atmosphere interactions. A deeper understanding of these interactions is essential to frame how key actors in the food system influence them. This knowledge is crucial for informing targeted regulations and stewardship initiatives. In the field of land-atmosphere interactions, atmospheric moisture flow reconstruction is central, and significant gaps remain in assessing the uncertainties of moisture tracking data and their alignment with underlying climatological reanalysis datasets—i.e., a

combination of past observations with weather forecasting models to generate consistent time series of climate variables. These uncertainties hinder the reliability of moisture tracking data for evaluating land-induced changes in hydrological flows and addressing policy-making questions. Addressing this uncertainty is essential for improving the robustness of assessments and ensuring that atmospheric moisture flow analyses can effectively inform sustainable water management and policy decisions.

This thesis contributes in this field by framing a reconciliation approach to match tracked estimates of flows from sources of evaporation to sinks of precipitation (and vice-versa) with climatological reanalyses of precipitation and evaporation volumes on the annual scale. The approach is developed at the country/ocean scale, at the sub-continental scale, and at the cell scale (0.5°). The application at different scales validates the scale-invariance of the approach and, especially, the computational effort of the application at the cell scale.

Structured in three parts, this thesis explores the virtual water trade assessment of TNCs (Part I), the estimation of global atmospheric moisture connections, and the interplay between virtual and atmospheric global networks (Part II), and outreach activities undertaken during the PhD journey in the field of knowledge transfer, societal engagement, and cultural empowerment (Part III).

Part I begins by focusing on the emblematic case of Brazilian soy (Chapter 2) and then expands to the broader South American supply chains of soy, corn, and coffee of major global TNCs (Chapter 3).

Part II investigates the interconnections between land, atmosphere, and water. A methodological framework is developed to reduce uncertainty and enhance the reliability of moisture tracking data estimations, using a mathematical approach—i.e., the Iterative Proportional Fitting (IPF). The first study in this part (Chapter 4) reconciles discrepancies and establishes a unique network of flow connections at the country and ocean scale. The following chapter (Chapter 5) extends the developed framework to the cell scale and releases a new annual dataset of global connections between sources of evaporation and sinks of precipitation at 0.5° spatial resolution. Chapter 6 bridges the virtual and atmospheric systems to deepen understanding of their interrelations by examining how the socio-economic system and natural atmospheric processes interact at the global scale.

Part III is dedicated to the activities addressed to knowledge transfer, societal engagement, and cultural empowerment undertaken by the author. Chapter 7 illustrates examples of knowledge transfer, provided through data and indicators to policy-making, and of societal engagement and cultural empowerment, provided by developing tools and activities to engage and empower consumers, farmers, and stakeholders.