Complex Connections: How Information Flow Networks Can Quantify Ecohydrological Interactions

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Ecohydrological systems comprised of soil, water and vegetation are intricately connected, and changes in one component can trigger feedback mechanisms throughout the network. Understanding how these complex interactions occur and propagate is challenging. To address this, Dr Allison Goodwell and Professor Praveen Kumar from the University of Illinois Urbana-Champaign have characterised information flow — a mathematical concept initially developed for communication systems — to better quantify and understand these interactions. Their research offers new insights into ecosystem responses, evolving precipitation patterns, and ecohydrological models, advancing our understanding of environmental dynamics.

A Novel Application of Information Flow to Ecohydrology

The processes governing ecohydrological systems are intricately connected through exchanges between atmosphere, soil and vegetation subsystems. Their interdependence on one another means that a change in the properties of one component can radiate throughout the network. For instance, strong rainfall will cause an increase in soil moisture, which may affect vegetation growth and, thus, atmospheric conditions, leading to more rainfall. Such complex interactions are often difficult to capture, and quantifying information flow provides a useful framework to describe connections within and between ecohydrological systems.

Information theory is a mathematical framework initially developed to study communication systems but has since proven to be a powerful tool in the Earth sciences. By examining how information is processed and shared among different variables, researchers are gaining new insights into complex ecosystems and weather patterns.

As discussed in their 2020 paper *Debates—Does Information Theory Provide a New Paradigm for Earth Science? Causality, Interaction, and Feedback*, Dr Allison Goodwell, Professor Praveen Kumar and collaborators discuss the use of information flow versus traditional approaches in understanding cause-and-effect interactions. Traditional approaches are often limited to correlations or linear dependencies in environmental processes, which may or may not indicate a real cause-effect relationship. Meanwhile, information shared among variables can be used to analyse more complex relationships with many interacting processes.

As such, information shared between variables can reveal relationships missed by other methods and categorise other relationships as non-causal. In exciting new studies, the researchers have applied this approach to better understand how ecosystems respond to environmental changes, how precipitation patterns are evolving, and how we can improve predictive models.

Understanding Ecosystem Responses to Rainfall and Drought

In a 2018 paper titled *Dynamic Process Connectivity Explains Ecohydrologic Responses to Rainfall Pulses and Drought*, the researchers investigated how ecosystems respond to variations in water availability, specifically focusing on rainfall pulses and droughts. This research used a Temporal Information Partitioning Network (TIPNet) to analyse the connectivity between environmental factors, including soil moisture, temperature, and exchanges of carbon and water between the land and the atmosphere.

They developed the TIPNet method to help break down and understand the connectivity between components of environmental systems. Within systems, a variable can be classified as a 'source' that may provide information, a 'target' that receives information, or both.

For instance, in a study looking at factors affecting the rate of plant growth, a source may be soil moisture, and the target may be a measure of plant growth. However, if the effect of plant growth on soil moisture is of concern, the plant growth could instead be considered a source of information to soil moisture, the target. If two sources (e.g., soil moisture and humidity) influence one target (e.g., plant growth), the knowledge of the sources reduces the uncertainty about the target, which is measured as mutual, or shared, information. To classify the nature of shared information, the method of 'information decomposition' can be used, which categorises the information flow from sources to target into three types:

- **Unique Information:** This is the specific contribution of each source individually (for instance, the influence that soil moisture has on vegetation growth).

- **Synergistic Information:** This is the additional predictive power gained when combining, for instance, soil moisture, temperature, and humidity. The combined knowledge of all three sources might provide a better prediction of vegetation growth than any individual source alone.
- **Redundant Information:** This is the overlap in the information provided by the sources. If both soil moisture and humidity measure aspects related to water availability, some of the information they provide about vegetation growth might be redundant.

Putting this into practice, at the Reynolds Creek Critical Zone Observatory in Idaho and the Southern Sierra Critical Zone Observatory in California, scientists examined how these information quantities change during and between rainfall and drought events. They found that after a period of heavy rainfall, the connectivity between soil moisture and carbon fluxes increased, indicating a stronger relationship between these variables following rainfall as plants respond to added moisture.

Conversely, during droughts, the connections between various environmental factors shifted, and a site with vegetation mortality showed different patterns of connectivity relative to a site where plants were able to access deep soil moisture. Such a holistic view of the interconnectivity of these dynamic processes is not possible without the lens of information flow pioneered by the scientists. By understanding these interactions under different environmental conditions, researchers can better predict how ecosystems will respond to changes in water availability, which is crucial for managing water resources and predicting ecological impacts.

Evolving Precipitation Patterns Across the United States

Dr Goodwell and Professor Kumar also demonstrate how recognising patterns in rainfall occurrence can help predict future rainfall. In their paper *A Changing Climatology of Precipitation Persistence across the United States Using Information-Based Measures*, they examine how precipitation patterns vary and how they have changed over time, using information metrics to measure uncertainty and predictability.

To achieve this, information employed from theory-based methods assessed daily precipitation patterns across the U.S. and how those patterns could be ordered or predicted versus more random. The researchers quantified this predictability using mutual information, which measures the amount of information shared between past and current precipitation occurrences, thereby evaluating how past data can inform future conditions. Analysing extensive long-term precipitation records from different climate regions allowed the exploration of changes in predictability over time and the comparison of spatial variability between regions. For instance, the western U.S. exhibited higher predictability, with more information shared between recent and current states, while the eastern U.S. showed greater variability and more dominant long-term patterns. This application of information-based measures revealed regional and seasonal variations in precipitation predictability, highlighting areas with trends in these weather patterns. This enhanced understanding of precipitation persistence provides valuable insights into how climate change impacts regional weather dynamics regarding precipitation rather than only extreme events. The findings are crucial for refining predictive models and informing water management strategies, particularly in regions vulnerable to changing precipitation patterns.

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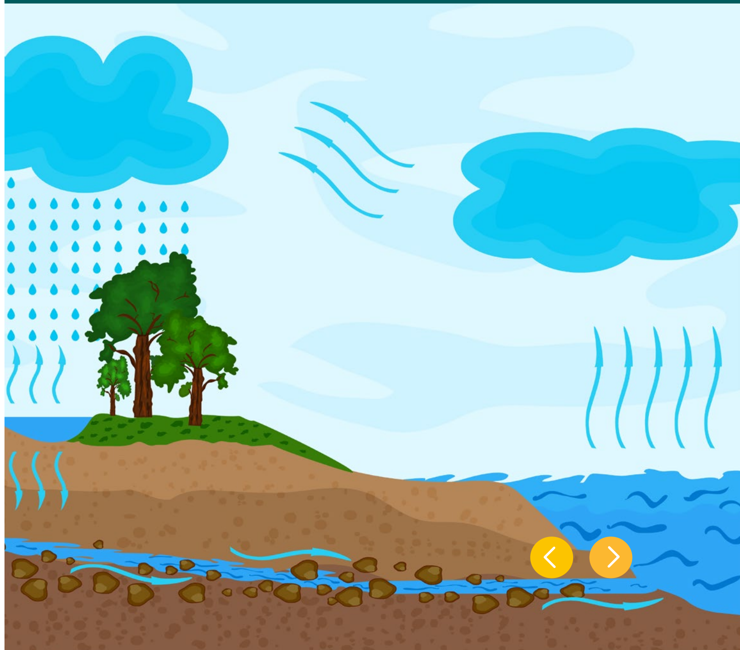

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To achieve their goal, Dr Goodwell and Professor Kumar compare several ecohydrologic models to explore how different structural designs and source properties influence information flow and the accuracy of predictions.

Evaluating Ecohydrological Models with Information Theory

Among the scientific community, ecohydrologic models are crucial tools that combine ecological and hydrological processes to help scientists and environmental managers predict conditions related to ecosystems and carbon, nutrient, and water cycles, both in the present and under future climate change.

In *Source Relationships and Model Structures Determine Information Flow Paths in Ecohydrologic Models*, the researchers showcase the application of information theory to evaluate ecohydrologic models. The authors demonstrate how the design and configuration of ecohydrologic models affect how information is processed and transmitted within them.

Here, Dr Goodwell focuses on two key aspects: model structures and source dependencies. Model structures refer to the mathematical frameworks that define how different components of the system — such as rainfall, soil moisture, plant growth, and water flow — are linked together, for instance, in the form of equations in the model. As previously described, sources are variables within a system that influence a target (such as soil moisture on plant growth). Source dependency refers to the connectivity between two sources, inputs to a given ecohydrological model. For example, an evaporation model may have sources that include soil moisture, temperature, and humidity, which may be tightly synchronised or mostly unrelated.

To achieve this, several ecohydrologic models are compared to explore how different structural designs and source properties influence information flow and the accuracy of predictions. This involves mapping the flow of information between sources and towards targets to identify connections that most strongly influence model behaviour. Furthermore, the study includes synthetic data (artificially created data for testing purposes) and real-world (i.e., observed) data to help form a comprehensive understanding of how model structures and dependencies impact predictions.

The results highlight that the structure of the model — how it is built and the relationships it defines between variables — significantly impacts which variables are most influential, and how information is propagated through the model. However, the sources, which are often observed measurements, also impact this information flow.

This finding is critical because it suggests that even slight changes in model design or synchronisation between sources can lead to different outcomes, affecting decision-making processes related to water resource management, ecosystem conservation, and climate impact studies. By developing new ways of exploration, such as networks of interactions based on information flow, inaccuracies in model predictions arising from existing methods may be exposed and potentially mitigated.

Is Information Flow a Framework for Revealing Complex Interactions?

The characterisation of information flow among variables involved in natural systems has created new avenues for understanding and predicting complex systems. By examining how information flows between ecohydrological variables and how different factors interact, researchers are gaining valuable insights into how ecosystems respond to changes, how precipitation patterns evolve, and how to improve predictive models.

Information flow networks provide a valuable framework for analysing environmental data and offer new approaches to understanding interdependencies and managing these systems. It helps researchers uncover the intricate relationships within ecosystems and weather patterns, leading to better predictions and a deeper understanding of how environmental changes impact natural and human systems. If research, such as that of these examples, continues to leverage and improve upon this framework, it may allow more nuanced evaluations of our Earth system, furthering our knowledge and enhancing our ability to address environmental challenges. By identifying and integrating measures of information flow into environmental research, we are better equipped to manage and adapt to the ongoing changes in our environment.

MEET THE RESEARCHERS

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Dr Allison Goodwell is a visiting research scientist at the Prairie Research Institute, University of Illinois. She earned a Bachelor of Science in Civil Engineering from Purdue University in 2010, then a Master of Science in 2013 and a PhD in 2017, both from the University of Illinois. Following this, she held the position of Assistant Professor in Civil Engineering at the University of Colorado Denver from 2018 to 2023. Dr Goodwell's current research is centred on understanding causal interactions and dependencies within complex ecohydrologic systems, employing advanced models and data analysis techniques, and she has an extensive publication record in this area. She has supervised numerous undergraduate and graduate students, and has secured research funding from the National Science Foundation (CZ Cluster: Critical Interface Network in Intensively Managed Landscapes) and NASA (New Investigator Program).

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Professor Praveen Kumar holds a BTech from the Indian Institute of Technology, Bombay (1987), an MS from Iowa State University (1989), and a PhD from the University of Minnesota (1993). Following his tenure as a research scientist at NASA's Goddard Space Flight Center, he joined the University of Illinois in 1995 as a faculty in the Department of Civil and Environmental Engineering. His research deals with Hydrocomplexity, the quantitative understanding and prediction of emergent patterns of form and function that arise from complex non-linear multi-scale interactions between soil, water, climate, vegetation and human systems, and how this understanding can be used for innovative solutions to water and sustainability challenges. He has made extensive, deep and signature contributions pertaining to information theory in geosciences, biosphere-hydrosphere interactions, multi-scale variability of hydrologic processes, hydro-geomorphology and hydroinformatics. He is the leader in the study of Critical Zone in human-modified environments. He presently serves as the Executive Director of the Prairie Research Institute (PRI), which houses all five of the Illinois State Scientific Surveys. He served as the Director of NSF-funded (IMLCZO) Intensively Managed Landscapes Critical Zone Observatory (2013–2021) and presently serves as the Director of NSF-funded (CINet) Critical Interface Network in Intensively Managed Landscapes (2020–2025).

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FUNDING

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FURTHER READING

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