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Fluctuations shape looping networks?

Understanding how transport networks, such as river systems, form and evolve is crucial to optimizing their stability and resilience. It turns out that networks are not all alike. Tree-like structures are adequate for transport, while networks containing loops are more damage-resistant. What conditions favour the formation of loops? Researchers from the Faculty of Physics at the University of Warsaw and the University of Arkansas sought to answer this question. The findings, published in "Physical Review Letters," show that networks tend to form stable loop structures when flow fluctuations are appropriately tuned. This finding will allow us to understand the structure of dynamic transport networks better.

Transport networks, like blood vessels or river systems, are essential for many natural and human-made systems. Understanding how these networks form and grow is crucial for optimizing their stability and resilience. Even seemingly similar flow systems, like river deltas, may include different morphologies. The outflow from Wax Lake in Louisiana, USA seems to branch into a treelike pattern with smaller river outlets reaching the Atlantic Ocean. The Ganges-Brahmaputra River Delta in Bangladesh, on the other hand, shows a looplike topology, with numerous channels interconnecting primary branches. What makes these two systems different is the magnitude of flow fluctuations, driven by an interplay of river discharge and tidal flows.

The question of what environmental conditions might promote the formation of loops over treelike structures has inspired a collaboration of scientists from the Faculty of Physics of the University of Warsaw, Poland, and the University of Arkansas, USA, to investigate the stability of looplike topologies in flow networks. Results of the research, published in "Physical Review Letters," show that networks tend to remain looplike when the flow fluctuations remain tuned in a particular way.

"Simple growth rules can often lead to fascinating patterns. Tree-like structures are effective for transport, but networks that contain loops are more resilient to damage," says Prof. Piotr Szymczak from the Faculty of Physics of the University of Warsaw, a co-contributing author of the study. "Understanding the necessary conditions for the emergence of loops in evolving networks is our long-term goal."

"River networks can look remarkably different depending on the river and the sea – geospatial data provides us with visual evidence on the changing morphologies of river deltas and with new data being collected on flow characteristics we are trying to learn more about the dynamics of their evolution, particularly in the time of rapid climate change," remarks Prof. John Shaw from the University of Arkansas, who spent his sabbatical at UW in Poland thanks to the Fulbright Research Award. "This publication was born from the fusion of geological observations, equations of sedimentology and mathematical methods of physics."

"Our collaboration started focused on rivers, but the observations generalize to a remarkably large class of transport networks," says Radost Waszkiewicz, the leading co-author of the paper and a PhD student at the Faculty of Physics UW.

The scientists have discovered that the stability of loops in these networks depends on the interplay between geometric constraints and fluctuations in flow. They found that loops require fluctuations in the relative size of flow between nodes, not just temporal variations in flow at a single node and that the loops are more stable when the fluctuations are neither too small nor too large relative to the constant flow component.

"Should the fluctuation pattern change because of external factors such as human intervention or climate change, new loops inside transport networks might appear or disappear, transforming the network's form," concludes Prof. Maciej Lisicki from the Faculty of Physics, UW. We hope that this observation will entice more precise measurements in natural systems and will take us one step further in understanding the dynamic remodelling of transport networks."

Faculty of Physics of the University of Warsaw

Physics and astronomy at the University of Warsaw appeared in 1816 as part of the then Faculty of Philosophy. In 1825, the Astronomical Observatory was established. Currently, the Faculty of Physics at the University of Warsaw consists of the following institutes: Experimental Physics, Theoretical Physics, Geophysics, the Department of Mathematical Methods in Physics, and the Astronomical Observatory. The research covers almost all areas of modern physics on scales from quantum to cosmological. The Faculty's research and teaching staff consists of over 250 academic teachers. About 1,100 students and over 170 doctoral students study at the Faculty of Physics UW. The University of Warsaw is among the 150 best universities in the world, educating in the field of physics according to Shanghai's Global Ranking of Academic Subjects.

SCIENTIFIC PUBLICATION:

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GRAPHIC MATERIALS:

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Figure 1: Estuaries of rivers into the ocean can take various forms. (left) The delta of the Ganges and Brahmaputra rivers at the mouth of the Indian Ocean consists of channels forming loops that surround hundreds of islands. (Source: @ESA European Space Agency), (right) The mouth of a river from Wax Lake in Louisiana, USA, into the Atlantic Ocean is similar to that of a tree, in which the main stream divides into smaller branches. (Source: National Science Foundation, Center for Earth-Surface Dynamics).

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Figure 2: (A) Gastrovascular canal network of jellyfish *Aurelia aurita* distributing nutrients to its tissue. New canals appear on the outer rim of the jellyfish, grow towards its stomachs in the center, and reconnect to the existing parts of the network, creating many loops. Source: Stanisław Żukowski, Faculty of Physics, University of Warsaw & Laboratoire Matière et Systèmes Complexés, Université Paris Cité. (B) Blood vessels on the retina of the human eye form a dense network in which neighboring vessels have multiple connections, resulting in numerous loops. (Source: Dr. Graeme Birdsey and Prof. Anna M. Randi, Imperial College London).