Researcher finds cataracts and turbulence that seem to slow water's flow actually facilitate it

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When a stream of water strikes a flat surface, it forms a smooth disc of water before suddenly switching to turbulent runoff. The phenomenon helps water transfer its overall momentum. Credit: Duke University

Since 1996, Duke Engineering Professor Adrian Bejan has demonstrated numerous natural phenomena that validate his constructal theory in practice.

In short, the theory states that all flow systems, animate and inanimate, evolve in such a way as to provide greater access to what flows. This kind of flow typically takes the shape of a few large conduits attached to many smaller vessels, whether the phenomena be root systems of trees, effluent branches of river deltas, or the bronchial tubes that bring oxygen into the lungs.

He's even gone as far as to show its manifestation in the hierarchical nature of extraterrestrial objects, wealth distribution throughout a society and the evolution of the world's animal kingdom.

But within the past couple of years, two papers caught Bejan's attention that seemed to contradict the theory, at least on the surface, and made him curious.

One from CalTech investigated a phenomenon that Bejan witnessed himself on a regular basis just outside of his driveway. When water runs down an inclined surface that can be eroded away, it doesn't form a single, uniform channel; it creates a series of cascading pools that seem to hinder its flow rather than help it.

In the other paper, researchers from Cambridge investigated the nature of hydraulic jumps, which anyone with a flat sink has seen firsthand. When a stream of water hits a relatively large, flat surface, it spreads out in a smooth disk before suddenly giving way to a thicker, turbulent runoff. While scientists had long believed that this was caused by the effects of gravity, the Cambridge team showed that it is created entirely from surface tension and viscous forces balancing the momentum in the liquid film.

These two papers made Bejan consider a third potential contradiction—a thin sheet of water running down an inclined hard surface. As anyone watching rain flow down a driveway or sidewalk can see, the water forms a series of ridges running across the flow's direction. These lines are thick buildups of turbulent, rolling water waves that appear to hinder the flow.

With these three seeming contradictions in mind, Bejan put the constructal law to the test by exploring a series of simple physics models. As the results published the *ASME Open Journal of Engineering* show, despite appearances to the contrary, these phenomena improve the flow, as the constructral law predicts.

"These papers exploring phenomena that I see at home on a regular basis made me question the theory," said Bejan, the J.A. Jones Distinguished Professor of Mechanical Engineering at Duke. "But when I sat down and ran through the equations, I realized these effects are their own animal."

Solving the apparent contradiction in all three systems essentially comes down to a single fact; water travels with more momentum in a turbulent freefall than it does flowing smoothly over a surface.

For the sink-based hydraulic jumps, Bejan found that, while it may seem more efficient for water to spread out in a smooth disk, a thicker, turbulent layer actually increases the flow of momentum across the fluid layer. The hydraulic jump is a visual display of the transition to turbulent flow, and that turbulence, according to Bejan, is predictable and no longer a mystery.

Bejan then puts together a long list of features of turbulent flow predicted by invoking the constructal law.

In the case of the hard inclined surface, Bejan draws a diagram and explores the forces at work, including friction working against the water as it flows. He found that the roll waves are self-created "cliffs" that allow the water to roll over and fall freely for a short distance, increasing the momentum of the water and thus its overall flow rate.

A similar method of action is responsible for the series of cascading pools, because water falls over a dam more efficiently than when it slides down an incline. If water flows on an erodible surface, it will create a series of dams to fall over. This same idea can be seen in the design of pumped storage hydropower systems, where water is stored in a large reservoir and then released to travel through a turbine before reaching a second reservoir at a lower elevation. In these systems, the water travels vertically rather than on an incline because it produces a greater flow rate.

"The best physics can be proven with simple physics," Bejan said. "At first glance, these systems would seem to be impeding the system's flow. But it's not speed that's important, it's momentum transfer. These examples go to show how important it is for researchers to question observations and consensus."

More information: Adrian Bejan, Theory of Flow Access with Apparent Obstacles: Cascades, Jumps, Roll Waves, and Turbulence, *ASME Open Journal of Engineering*, 2022. DOI: 10.1115/1.4054473. asmedigitalcollection.asme.org … 15/1.4054473/1148219

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