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Science FINDINGS

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"Science affects the way we think together."
Lewis Thomas

Going with the Flow: New Insights into the Hydraulics of High-Energy Fluids

Brian Romans

Observing wave patterns in a sandbed stream flowing into the Pacific Ocean led to an "Eureka!" moment for research hydrologist Gordon Grant. The resulting theory of critical flow may fundamentally transform estimations of river and flood flows in wilderness areas, rivers without gauge networks, and through the use of satellite imagery instead of gauges.

Discovery consists of seeing what everybody has seen and thinking what nobody has thought.
—Albert Szent-Györgyi von Nagyrápolt, Hungarian biochemist

Among Gordon Grant's earliest memories is a fascination with water flowing downhill; he was enchanted by the streams that he and his father came across while hiking in the forest. Later, as a river guide, he sought out rivers with rapids and white-capped waves. That Grant chose a career about water is no coincidence; in 1983, he joined the U.S. Forest Service Pacific Northwest Research Station as a research hydrologist.

In the early 1990s, while visiting the Oregon coast with his wife, Grant stopped to watch small headland streams that were flowing onto a steep sandy beach and into the ocean. The miniature waves in the streams caught his attention. From a memory still vivid more than 20 years later, Grant recalls that they had a certain dynamic. The waves grew higher and higher before they broke and flattened, a transformation that lasted less than a minute, then repeated itself.

"Now what's going on here?" he wondered. "Why is it doing this?" As Grant continued to watch the white-capped waves that would form and disappear, he had an epiphany.

IN SUMMARY

Municipal water managers need to know if water will be reliably available from watersheds. Civil engineers need to calculate stream discharge to construct bridges to withstand 100-year floods. A hypothesis proposed in 1997 by Gordon Grant, a research hydrologist with the USDA Forest Service Pacific Northwest Research Station, underlies a method for getting this information from rivers without gauge networks or long-term flow data. Since then, laboratory experiments and field measurements have validated the hypothesis to the degree that it may now be considered a theory.

Critical flow *is a unique state of flow for high-energy rivers. For rivers or streams at critical flow there is a direct relationship between a stream's depth and velocity: if the channel's depth is known, the stream's velocity can be calculated and vice versa. With these two measurements, the discharge of a high-energy stream can be calculated at critical flow. By applying this method after floods, it is possible to calculate the discharge on ungauged rivers and determine if it was a 10- or 100-year flood event. This information is critical for flood risk-reduction efforts.*

Studies are underway to determine if the theory also applies to lava flows, while other researchers have used the theory to calculate ancient flood flows on Mars and Jupiter's moon, Titan.

"I realized that this stream was oscillating around critical flow," he explains. "When the streambed was flat, the flow would accelerate. As this happened, the streambed began to deform, which caused the system to become unstable and resulted in standing waves. The flow of water and energy through these wave forms, in turn, eroded the streambed and returned it to a flat condition, where the cycle repeated."

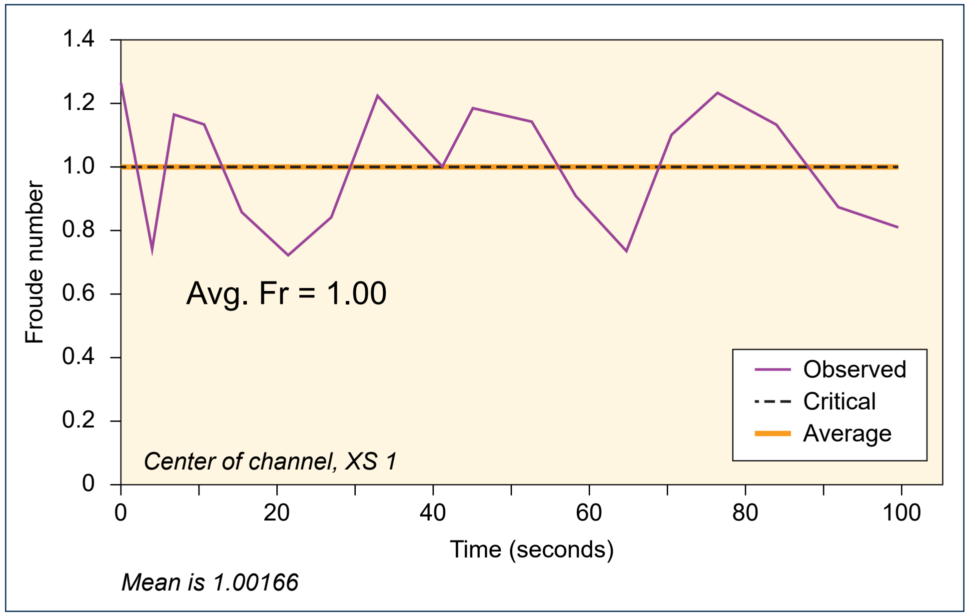
Why is this significant? As Grant would later discover, in these energetic streams, the physics underlying the movement of water in relation to its streambed is a key to understanding fundamental stream properties that can be used to calculate stream discharges during floods or on ungauged streams. This is critical information sought after by municipal water managers, civil engineers, and others.

What Moves a Mountain Stream?

Hydraulics is the study of how liquids move through channels or pipes—not to be confused with hydrology, which is the study of the water cycle, both above and beneath the Earth's surface. According to Grant, there's a long history of scientists studying rivers, both their hydraulics and hydrology, to understand the mechanisms, time scales, and ways in which they change.

"A river has many ways of changing," he explains. "It can get shallower or deeper. It can go faster or slower. Its channel can become steeper or gentler. The material it's moving, such as rocks or woody debris, may move more readily or become deposited. Sediment deposited on the bed can become larger or finer."

Physics drives these changes. For example, if a river is dammed, the lack of sediment flowing downstream will typically result in the river becoming deeper and narrower because the river is cutting into its bed to restore its depleted sediment load. If a river's flow discharge increases during a flood, the river has enough energy to overflow its banks and carve out a new channel.



Variation in the Froude number (Fr) measured over time in a sandbed channel similar to cover photo. The flow oscillates between sub- and supercritical flow, averaging at critical flow (Fr = 1).

Although these responses are understood and can be modeled, there are basic hydraulic principles that remain unclear. "What we don't have are general principles that explain why a river will do this or that in a given situation," Grant says. "What we want is to predict how a river will adjust its banks and bed in response to changes in how much water and sediment it has to carry."

These changes may be driven by the kinetic energy within the river. When the water has low kinetic energy—picture the slow-moving Mississippi River—the flow in the river is considered subcritical. Another way to determine if a river is subcritical is by observing its waves. When a rock is thrown into a slow-moving river, the waves ripple outward in an oval. Some waves move upstream but more move downstream with the current. In contrast, when a river has high kinetic energy—picture the water flowing over the face of a dam—the flow is considered supercritical. Throw a rock into a supercritical flow and no waves will travel upstream; they are all swept downstream in the fast-moving current.

The ratio between the speed of the water and the speed of waves moving through the water is called the Froude number. William Froude

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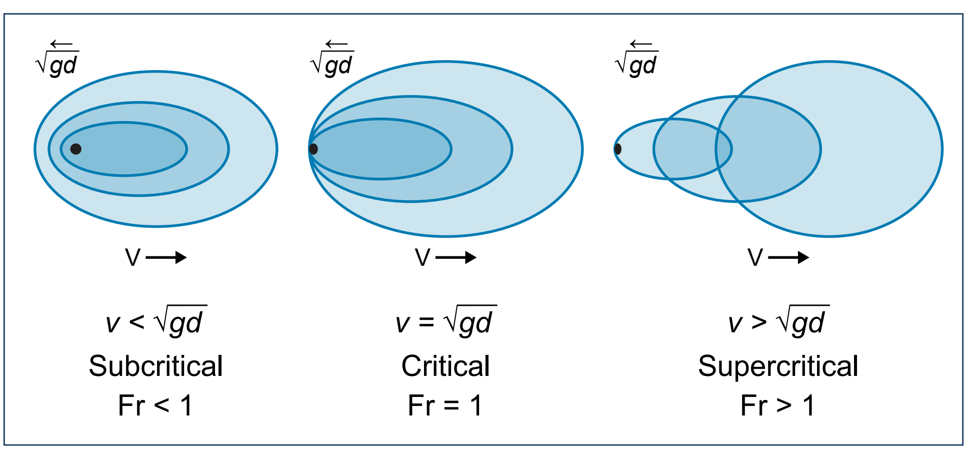


A schematic of wave patterns from a rock thrown into water moving at different speeds illustrates Froude's number (Fr), which is used to determine if flow is subcritical (slow; Fr is less than 1), critical (Fr equals 1), or supercritical (fast; Fr is greater than 1). V = water velocity, g = gravity, d = hydraulic depth.

was an English engineer and naval architect in the mid-1800s who discovered the relationship between the speed of an object, such as a ship, moving through the water and the water's resistance to that object. When water is subcritical, the Froude number is less than one; when water is supercritical, the Froude number is greater than one.

A river can have sections in which it fluctuates above and below a Froude number of one. Where this occurs, the subcritical water and supercritical water collide, and the kinetic energy within the supercritical water must be released in what is called a hydraulic jump.

"Picture a fast-flowing mountain stream with large rocks just barely below the water," says Grant. "Just downstream of these rocks one typically sees a white foamy wave —that's a hydraulic jump. Kayakers and rafters call it a 'hole.' The water flowing over the rock is supercritical and the water further downstream of the rock is subcritical. This foamy wave is the way the energy in the water is released."

Those white-capped standing waves that Grant observed in the streams along the Oregon coast were also hydraulic jumps. Because there was a pattern to the waves breaking and reforming, he inferred that the flow in the stream was oscillating, and the bed was adjusting to maintain near critical flow—that is, the river was using the least amount of energy to move the maximum volume of water. When a river is at critical flow, its Froude number is one. When this occurs, depth and velocity are related by a simple mathematical expression: if you can measure a river's velocity, you know the depth without having to manually measure it, and vice versa.

As Grant worked through the mathematics behind the critical flow hypothesis, he realized that it offered an innovative way to calculate the flow discharge of high-energy rivers with a steep gradient, specifically mountain streams. In 1997, he published a paper outlining the methodology behind the hypothesis but received little to no response. As other research projects became priorities, Grant placed the critical flow research aside. It wasn't until 2015 when Colorado State University named him the Borland Lecturer in Hydraulics, an honor that came with having to prepare a speech, that Grant realized how widespread the critical flow hypothesis had become. "Much to my relief, in a sense," he says, "I discovered that there's a growing body of data to support it."

The best test came in 2019, when researchers in Switzerland tested the critical flow hypothesis in a laboratory setting and confirmed the underlying physics influencing these mountain streams. Grant recalled being surprised when asked to review their results and was gratified to hear that their work validated his insight over two decades ago. "I feel I can now speak of the critical flow concept as a theory, not a hypothesis," he says proudly.

KEY FINDINGS

- The critical flow theory suggests that mountain streams adjust their beds and banks to maintain a hydraulic condition called critical flow. This is an energetic optimum whereby the maximum volume of fluid is moved with a minimum amount of energy.
- The validity of the theory has been demonstrated by highly detailed measurements in laboratory experiments, direct measurements, and model calculations of flood flows in diverse environments, including flash floods, incised gullies, alluvial fans, and on the surface of Mars.
- Adoption of the critical flow theory has the potential to fundamentally transform estimating river and flood flows in wilderness areas, rivers without gauge networks, and through the use of satellite imagery instead of gauges.

Calculating Mountain Stream Flows

Being able to calculate current stream flow is critical for understanding how stream discharges within a watershed may change over time. Land managers need this information to calculate water availability. Engineers must consider 100-year floods when designing bridge crossings so the bridge won't wash out. When designing stream restoration projects, knowing discharge volumes ensures that the installed log jams or other in-channel structures will remain in place and won't be ripped out by flood waters.

There are a number of scenarios in which the critical flow theory has proven invaluable to managers and researchers in other disciplines. In the western region of the United States, mountain streams feed the watersheds that supply water to lowland cities and communities. Unlike the rivers downstream that are gauged, very few of these mountain streams have gauges.

"It's very difficult to make measurements on a fast-moving mountain stream," says Chris Magirl, a research hydrologist with the U.S. Geological Survey (USGS). "Establishing a gauge that can operate 365 days a year through low flow, medium flows, and big floods is a challenge. In a lot of these high-energy mountain streams, our gauges just get destroyed when we have a large rain event."

Sending field crews to collect measurements in remote mountain streams during flood conditions isn't feasible or safe. Consequently, Magirl explains, "it's an ongoing challenge to come up with different techniques to understand the hydraulics of mountain rivers and how much water they are pushing down toward the lowlands."

Grant's critical flow theory offers a way to calculate the flow volume on these ungauged rivers. "If a mountain stream's Froude number is one, all those complex equations trying to estimate discharge as a function of water surface elevation go away," Magirl says. "A hydrologist just needs to measure the depth of flow and they will know the discharge."

USDA Forest Service

Winter flooding and a washed out road in the Umatilla National Forest, Oregon. The critical flow theory can be used when designing in-channel structures and projects that resist erosion and maintain long-term stability.

Calculating Lava Flows

Although the critical flow theory was conceived with mountain streams in mind, it's now being applied to another well-known geological fluid. In 1996, Grant caught up with longtime colleague, Katharine Cashman, at her lab at the University of Oregon where she was a professor in the Department of Geological Science. Cashman was showing Grant videos of the 1984 eruption of Mauna Loa on Hawai'i Island, and immediately he recognized a pattern in the flowing lava. "I told Kathy those are standing waves in lava flows!" he explains.

"Gordon asked me if anyone had worked on the flow dynamics, particularly on what appeared to be both standing waves and diagonal shocks," Cashman says. "We then started to explore the possibility that they could represent critical flow and what the implications would be. I immediately recognized that if critical flow theory could be applied, it would give us a rapid way to measure effusion rate."

The effusion rate is the amount of lava being erupted at a given time. It's calculated by taking the average velocity times flow depth by flow width; however, it's very challenging to measure a lava flow's depth because of the intense heat, opacity of the lava, and swiftness of the lava flow. Employing the critical flow theory would provide an invaluable workaround for volcanologists and emergency managers when calculating how far lava flows will travel and how fast the flows will advance.

"We can measure the flow width and now, particularly using drones, can measure the surface velocity," Cashman says. "Critical flow theory and standing wave analysis could help us to determine flow depth and average velocity."

However, as was the case before, other research became a priority; Cashman and Grant tabled their idea until the eruption of Kīlauea in May 2018.

During the eruption, Hannah Dietterich, a research geophysicist with the USGS Alaska Volcano Observatory and former graduate student in Cashman's lab, was tasked with running lava flow forecasts for the emergency managers to use when assessing where evacuations or road closures were needed. She was familiar with the critical flow theory as it related to standing waves, and about a month after the eruption began, she noticed standing waves in the lava flow.

"I immediately started using that Froude number to estimate what the depth might be," Dietterich says. "It offered an independent way to estimate the depth that gave us a lot more confidence in our estimates of lava effusion rate."

Jon Major, a research hydrologist with the USGS Cascades Volcano Observatory and frequent research collaborator with Grant, was also stationed at the eruption and noticed the standing waves as well. "The standing waves in the lava flow were impressive," he recalls. "They were two to three meters high."

When Grant learned from Major of these standing waves, he wanted to jump on a plane to Hawaii to see the phenomena for himself. Although Grant was unable to fly out, Major supplied observations and footage of the lava flows. Major also shared with Dietterich another independent option for determining

LAND MANAGEMENT IMPLICATIONS

- The critical flow theory has direct bearing on regulatory issues such as flood insurance and flood risk-reduction efforts. It can be used to determine if a recent flood was a 10- or 100-year event.
- Applying the critical flow theory simplifies the process for estimating flood magnitudes from obtainable measurements such as depth.
- The critical flow theory can be used when evaluating the stability of channel beds and banks, designing in-channel structures, and in projects that resist erosion and maintain long-term stability.


USGS Hawaiian Volcano Observatory

During the 2018 Kīlauea eruption in Hawai'i, standing waves were clearly visible in the lava flow near the vent. A team of volcanologists and hydrologists is testing to see if critical flow theory can be used to calculate lava flow discharge.

the depth of the channel by measuring the wavelengths of the standing waves.

Collectively, the team realized that it was time to fully explore the theory that Grant and Cashman had discussed in 1996. "And from there, the project has just grown and blossomed," Major says.

Operating under the assumption that the critical flow theory applies to lava flows and using high-quality drone-shot video footage of the lava flows to calculate velocity and depth, the team is calculating the lava effusion rates during the 2018 Kīlauea eruption.

"Lava flows are very viscous, and their density is different," Dietterich says. "They operate in a very different regime than water, and it's not necessarily obvious that the simplified fluid dynamics of rivers applies to lava flows."

However, based on their preliminary results, Major says, "We have some confidence that these hydraulics theories and relationships for water seem to be holding for the lava flow."

Measuring Critical Flow in the Solar System

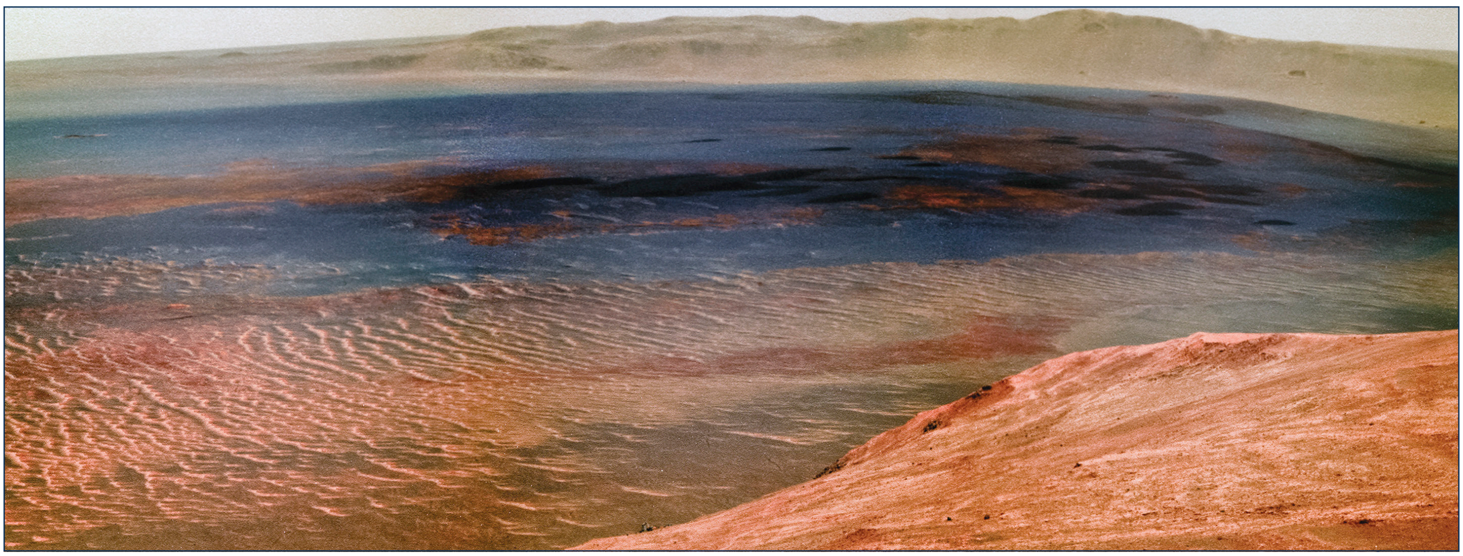
Cashman also sees a value in exploring the use of the critical flow theory to determine flow rates of other viscous flows, such as mudflows, and one team of researchers went even further. They applied the theory to the liquid methane rivers on Jupiter's moon, Titan. When accounting for the differences in fluid densities and gravity, the estimates were reasonable and provided an approximation of possible discharge volumes.

Another team of researchers used the theory to calculate the ancient flow discharge of water on Mars. Although this research is intriguing, "The problem with the Mars research is it's not a solid test of the idea," Grant admits. "The researchers were seeing if they could use this as a constraint to help estimate what the floods were. When they did that, they got reasonable estimates."

When reflecting how his critical flow hypothesis evolved from a hypothesis to a theory, from minimal response upon publication to now being widely cited in scientific journals, Grant says, "It has been a real interesting example of how the marketplace of ideas works to advance ideas that have staying power and those that don't fall by the wayside. It's rare you get an explicit testing of an idea, and that's something I think is cool."

"Every great discovery or decision comes by an act of divination. Facts are fitted around afterwards."

—David Herbert Lawrence,
British writer



NASA Jet Propulsion Laboratory
Processing by Elisabetta Bonora and Marco Faccin

Image of Mars from the rover Opportunity. Researchers used the critical flow theory to estimate ancient flows of water on Mars.

For Further Reading

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