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Science FINDINGS

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INSIDE

"Science affects the way we think together."

Lewis Thomas

The Spirit Lake Dilemma: Engineering a Solution for a Lake With a Problematic Outlet

Rhonda Mazza

Spirit Lake, with Mount St. Helens, Washington, in the background (2015). A debris avalanche triggered by a volcanic eruption on May 18, 1980, blocked the lake's natural outlet. A tunnel was built to safely remove water from the lake and minimize the risk of catastrophic flooding to communities downstream. Maintaining the tunnel is expensive, so long-term solutions are being explored.

"When you want to know how things really work, study them when they're coming apart."

—William Gibson, writer

When Mount St. Helens erupted on May 18, 1980, its northern flank collapsed, triggering the largest landslide in recorded history. A good portion of this debris avalanche tore through Spirit Lake. Within moments, the lake was violently altered. The picturesque recreation site, home to youth camps and visitor lodges was gone. When the debris avalanche hit the lake, it caused a wave that scoured the northern slope of the lake basin. Hundreds of logs from the pre-eruption forest can still be seen floating in the lake. When the dust settled, the lake had roughly doubled in surface area but was much shallower; the debris deposit raised the lake bed nearly 200 feet. The debris also blocked Spirit Lake's outlet to the North Fork Toutle River.

"What had been a lake with a babbling trout stream as an outlet suddenly became a closed basin," explains Gordon Grant, a research hydrologist with the U.S. Forest Service Pacific Northwest Research Station.

IN SUMMARY

The Mount St. Helens eruption on May 18, 1980, fundamentally transformed the surrounding landscape. The eruption triggered geophysical processes that are still unfolding. A debris avalanche caused by the eruption, for example, blocked the outlet from Spirit Lake. To prevent the rising lake level from breaching the blockage and potentially flooding communities downstream, the U.S. Army Corps of Engineers built an outlet tunnel to maintain safe lake levels. However, the tunnel must be periodically closed for repairs, during which time the lake can rise precariously high.

In 2015, the Gifford Pinchot National Forest commissioned a study to assess risks associated with alternative outlet options. A team consisting of researchers from the U.S. Forest Service Pacific Northwest Research Station, the U.S. Geological Survey, and Oregon State University authored the study.

At the team's request, the U.S. Army Corps of Engineers conducted a dam-safety risk-assessment of long-term solutions: maintaining the existing tunnel, rehabilitating the tunnel, creating an open channel across the blockage, or installing a buried conduit across the blockage. The assessment determined that there is no risk-free way to remove water from Spirit Lake, but the likelihood is generally low that these solutions will fail. With this information, the Forest Service is moving forward with developing a long-term solution to managing the Spirit Lake outlet.

Within 2 years, the hazard of a closed basin was realized. Rainfall and melting snow were raising the lake level, and authorities feared that a catastrophic breach could result if rising lake waters reached the layer of erodible sand and silt within the debris blockage. In 1982, the U.S. Army Corps of Engineers (Corps) installed a temporary pumping station to stabilize the lake's level. Three years later, a more permanent solution was completed: a nearly 2-mile tunnel was bored through the volcanic bedrock bounding the western side of Spirit Lake to divert the water into the South Fork Coldwater Creek, a tributary of the North Fork Toutle River.

As the agency responsible for managing the Mount St. Helens National Volcanic Monument, the Forest Service also maintains the tunnel, which has performed as designed for more than 30 years. Yet like all infrastructure, it needs periodic maintenance; this means closing the tunnel to make repairs. "Over the years, the tunnel has experienced what the engineers describe as heave, which basically means there is a shifting of the rock constricting the tunnel and reducing its capacity," says Grant. "When this happens, it needs to be fixed because the tunnel is essential to maintaining lake levels."

Tunnel closures in 1995 and 1996 to perform such maintenance resulted in Spirit Lake reaching precarious levels. Jean Holmes, former forest supervisor of the Gifford Pinchot National Forest, recognized that increasingly costly repairs to maintain the tunnel were unsustainable, and that closures to repair it increased the potential risk of a breach. In spring 2015, she reached out to Grant, with whom she had previously worked on other projects, to ask if he could identify alternative outlets that were cost-effective yet could reliably divert water from Spirit Lake.

Although Grant hadn't conducted research at Mount St. Helens before, Holmes' request intrigued him. "It appealed to me in part because there was a science and management component to it," he says. "There was a certain urgency about it because they were having to fix things that were breaking."

Recognizing that a long-term solution was needed for the Spirit Lake outlet, members of Washington's congressional delegation wrote to the Chief of the Forest Service, the Assistant Secretary of the Army, and the Director of the U.S. Department of the Interior

KEY FINDINGS

- Under most circumstances, the current tunnel outlet has effectively maintained safe lake levels during both normal and historically large storm events. To date, Spirit Lake has never exceeded its designated maximum safe operating elevation.
- Despite the overall success of the existing tunnel, the potential for a breakout flood is significantly heightened if the tunnel is closed for an extended time for repair. The highest lake levels over the past 34 years are associated with three periods of extended closure for tunnel repair.
- Both modeling and geologic evidence indicate that breaching of the Spirit Lake blockage would be catastrophic. The resulting flood could inundate downstream communities to depths of 16 to 65 feet, resulting in substantial economic damages and possibly significant loss of life. Models are broadly consistent with mapped elevations of volcanic debris-flow deposits resulting from a breaching of an ancestral Spirit Lake about 2,600 years ago.
- There is no risk-free way to remove water from Spirit Lake. All failure sequences for all possible lake outlets involve a cascading sequence of events, each of which has a finite but difficult-to-quantify probability of occurrence.

Purpose of PNW Science Findings

To provide scientific information to people who make and influence decisions about managing land.

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United States Department of Agriculture

Forest Service

Tom Casadevall

An aerial view to the south of Mount St. Helens in 1982 as another lahar—melted snow and volcanic rock (think wet cement)—occurred. When the lahar encountered the debris blockage from 1980, part of it flowed into Spirit Lake (bottom left), while the rest flowed west into the Loowit Creek drainage that flows into the upper North Fork Toutle River.

Geological Survey (USGS) requesting that the Forest Service, the Corps, and the USGS prepare a report that outlined possible long-term options. In fall 2015, Grant was officially assigned the project, and he reached out to Jon Major, a research hydrologist with the USGS to join the team.

"It was very clear from the get-go that because I hadn't done that much work around Mount St. Helens, I needed someone who knew the territory very well," explains Grant. "Jon has been working at Mount St. Helens for almost 30 years. If we're going to do this project, it should be an interagency effort with the USGS."

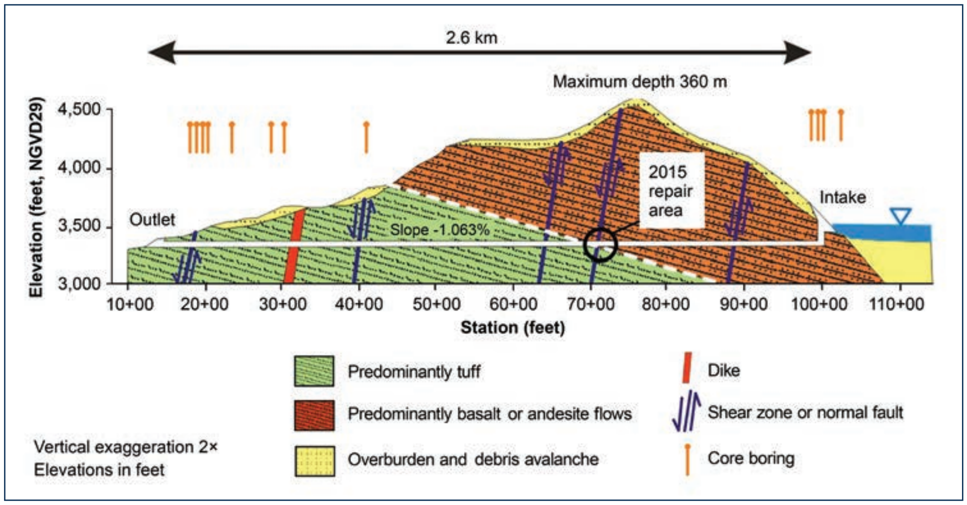
"When I received Gordon's request, I was more than happy and eager to collaborate with him," Major says. In 1981, a master's thesis project brought Major out to Mount St. Helens, and he's never left. His 30 years of research have focused on the evolution of the mountain's landscape, specifically how it changed the hydrology and geomorphology of the North Fork Toutle River system. "The 1980 eruption completely reset the alluvial landscape in front of the mountain, so we've been documenting how that landscape has evolved over decades," Major explains.

The third member of their team was Sarah Lewis, Grant's senior faculty research assistant at Oregon State University. Lewis had a strong geological background and an abiding curiosity about the project. "She was the glue that held us together," Grant says.

Analyzing and Quantifying Risk

To provide the Forest Service with information regarding sustainable, long-term management options, the team had several objectives to fulfill: evaluate the potential for tunnel failure and consequent catastrophic dam breach, evaluate potential risks associated with alternative lake outlets, evaluate potential consequences to downstream communities should a breach occur, and identify knowledge gaps that need to be addressed to fully evaluate the options available to management. The analysis would be synthesized into a report that the agency could use to inform its decisionmaking.

The team faced a tight deadline. Their analysis was part of a broader review that the National Academies of Sciences, Engineering, and Medicine (NASEM) was concurrently conducting of the Toutle River watershed, and their analysis would be part of NASEM's review. "Their role was to provide a framework for decisionmaking around this issue," Grant explains, "whereas ours was to burrow in on the technical issues that surrounded the consideration of any option."



Adapted from Grant et al. 2017

The nearly 2-mile outlet tunnel for Spirit Lake is bored through different kinds of rock. In some of the bedrock portion of the tunnel, the shifting rock constricts the tunnel and reduces its capacity. This was observed in 2015, and the tunnel was subsequently closed in 2016 and repaired. During the closure, the lake rose precariously high.

Soon into the project, Grant recognized that input was needed from a variety of agencies who had a role in the design and operation of the tunnel, chief among them the Corps. He learned of a "potential failure mode analysis" and a "semiquantitative risk assessment" developed by the U.S. Bureau of Reclamation and now used by the Corps to evaluate a dam's stability and the downstream consequences of its failure.

When Grant approached the agency, asking if they could perform these two analyses on Spirit Lake, they were intrigued by his request. However, there was a caveat: the Corps hadn't performed a potential failure mode analysis on a nonengineered structure before. Fortunately, the Corps thought it was possible, although being on a tight deadline they couldn't perform the indepth analysis that they usually would. After receiving the questions that Grant and his team were looking to answer—the consequences of a breach and the options available for safely diverting the water—the Corps and its analysts spent the next 4 months working through their analyses.

Meanwhile, Grant, Major, and Lewis conducted a literature review on geology and hydrology research published on Mount St.

Britton et al. 2016

The Spirit Lake outlet tunnel is inspected annually. This photo from 2015 shows where the tunnel floor had "heaved" in response to rock shifts.

Helens. This research provided a geologic and hydrologic context for interpreting the Corps' report, in addition to informing what research was still needed to fully understand the geology and hydrology of the landscape surrounding Mount St. Helens. During this time, their work proved even more necessary. Following a tunnel closure in early 2016, Spirit Lake's level nearly reached its maximum safe operating level for the third time. Yet, as Grant is quick to clarify, the risk of catastrophic failure was remote. It was this dichotomy that he says took a while to understand.

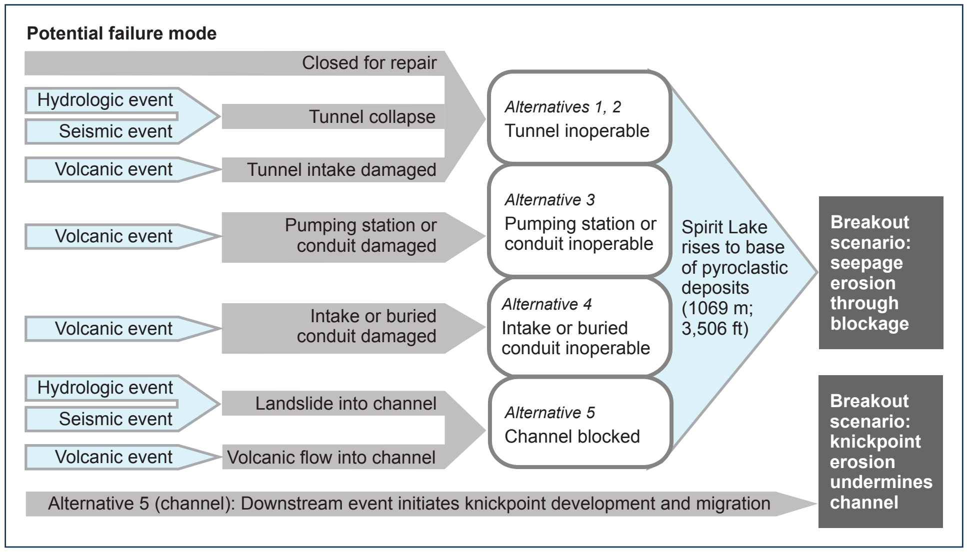
"When you think about a dam, you worry about a catastrophic failure in a matter of hours and that was not the dilemma with Spirit Lake," he explains. "If the tunnel failed, it doesn't mean a wall of water is imminent because the lake has to fill first. I had to understand the time scales over which a breaching of the blockage was actually a real problem."

And the geologic record reveals that the risk is real. Roughly 2,600 ± 150 years ago, an eruption unleashed a debris avalanche down the mountain's north flank and blocked Spirit Lake's outlet. When the inevitable breach of the blockage occurred, a mudflow, the largest that's been preserved at Mount St. Helens, inundated the area where the communities of Castle Rock and Kelso are now located.

"We know what the consequences of a breach are, and the consequences are rather dire," Major declares. "It's obvious we cannot allow the lake to breach the blockage."

This was the context with which the Corps' potential failure mode analysis and a semi-quantitative risk assessment were reviewed. The Corps identified four long-term outlet options: continued maintenance of the existing tunnel, a fully rehabilitated tunnel, a conduit buried across the blockage, or an open channel across the blockage. Together, both teams spent a week reviewing the options and discussing potential failure scenarios that could directly or indirectly result in these four outlets failing. These failure scenarios included the occurrence of a Cascadia megathrust earthquake, various eruption hazards, and changes in precipitation patterns in the watershed resulting from climate change. These what-if scenarios were then assigned one of seven failure likelihoods that ranged from remote to failure progression observed. In addition, each of these failure likelihoods was assigned a confidence level—low, moderate, and high—that indicated the team's confidence of the failure likelihood.

One such scenario for the existing tunnel was an extended tunnel closure that causes the lake level to rise to a precariously high level. During this hypothetical closure, an extreme hydrological event occurs that results in



Adapted from Grant et al. 2017

Schematic depiction of potential failure modes, outcome of failure mode on infrastructure, and ultimate potential consequence of outlet system failure.

Jon Major

Researchers look at past deposits from lahars in the Toutle River Valley. These deposits stem from an ancestral Spirit Lake that was dammed by debris avalanche(s) from an eruption of Mount St. Helens approximately 2,500–2,900 years ago.

uncontrolled flow into the tunnel, and the tunnel subsequently fails. Although this is a significant risk driver that could contribute to a breach, the likelihood of it happening is moderate with a confidence level of low. (A low confidence level means that the team needs more information to determine if they assigned the right failure likelihood category.)

As the team discussed the failure likelihoods of each outlet option, they found that, regardless of which long-term alternative solution was selected, there is no risk-free way to remove water from Spirit Lake. Each of the outlets has a finite likelihood of failure, although the probability that failure will occur is generally remote to low.

"Some options are more sensitive to volcanic events, while other options are more sensitive to hydrologic or earthquake events," Major explains. "Every one of them has some degree of risk affiliated with it related to these natural processes that have shaped our part of the country. It's this balancing act of selecting which one minimizes the highest probability risk the most."

For example, if the open channel outlet option was selected as a replacement to the existing tunnel, the probability that a potential blockage of an open channel could lead to a release of lake water is somewhat greater compared to the other options. However, an open channel has benefits that a tunnel does not, such as allowing lake water to drain more rapidly following a major flood, and it has fewer mechanical issues that could fail.

The analyses by the Corps provided crucial information Grant and his team needed for their report. Yet there was one complicating factor that Grant hadn't anticipated—the Corps considered its report for official use only and not for public dissemination, whereas any material provided to the NASEM was entered into the public record. Therefore, the Corps' potential failure mode analysis and semiquantitative risk assessment could not be provided to the NASEM directly. It took negotiating on both sides to agree on the level of detail that could be entered into public record, and in June 2017, the general technical report *The Geologic, Geomorphic, and Hydrologic Context Underlying Options for Long-Term Management of the Spirit Lake Outlet Near Mount St. Helens, Washington* was published by the Forest Service and presented to the NASEM.

Next Steps

In late 2017, the NASEM published *A Decision Framework for Managing the Spirit Lake and Toutle River System at Mount St. Helens*. This report, in conjunction with the general technical report, will help inform the Forest Service in choosing a long-term management solution for Spirit Lake.

Grant and Major are encouraged to see the Forest Service funding research projects that fill in the uncertainties their report identified. One of these uncertainties is understanding the geomorphic nature of Spirit Lake's debris blockage and its erosional sensitivity, which can have ramifications for an open channel outlet, according to Major. The Forest Service has contracted with the Corps to put in additional drill holes in select locations on the blockage to supplement data collected in the early 1980s.

"The Gifford Pinchot National Forest, to their credit, has gone through the uncertainties we identified, taken them seriously, and used them as a way of guiding their next moves for getting information," says Grant. "In many ways, it's been a good example of the handoff of research and technical information into the management sphere."

Another example of management handoff is Forest Service staff and emergency managers from surrounding communities conducting tabletop exercises to work through what-if scenarios involving the breaching of Spirit Lake so everyone is aware of their respective responsibilities should a disaster occur.

It's this management handoff, along with the collaboration of multiple agencies and disciplines, that Grant considers a great outcome of this project. "Beyond all the science issues that we talk about, the most important aspect is that this project was part of a much larger, multiagency, multi-institutional effort," he says. "Research has played an important role in establishing what we know and what we don't."

"The method of scientific investigation is nothing but the expression of the necessary mode of working of the human mind."

—Thomas Henry Huxley, biologist

LAND MANAGEMENT IMPLICATIONS

- Possible long-term approaches for providing a safe lake outlet include the existing tunnel (with expected ongoing maintenance and repair), a fully rehabilitated tunnel, a conduit buried across the blockage, or an open channel across the blockage. Using the U.S. Army Corps of Engineers standardized dam-safety risk-assessment procedure, these approaches were analyzed for their effectiveness and risk of failure.
- Overall, the probability that a failure of any alternative outlet will lead to catastrophic breaching of the blockage is generally quite low. However, the probability that a potential blockage of an open channel could lead to a release of lake water is somewhat greater, although an open channel has benefits that a closed conduit does not.
- The alternative outlets considered generally required some external driver (i.e., landslide, volcanic flow, seismic event, extremely large inflow of water) to render an outlet inoperable and allow for lake rise and a breakout flood.
- This risk assessment has significant uncertainties. Should one of three principal regional hazards (floods, earthquakes, eruptions) occur, it could alter the landscape or debris blockage in unpredictable ways. These uncertainties must be borne in mind when contemplating the utility of any potential drainage outlet.

Writer's Profile

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For Further Reading

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U.S. Bureau of Reclamation

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