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Seamless numerical simulation of a hazard cascade in which a landslide triggers a dam-breach flood and consequent debris flow

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Abstract

Numerical simulations of hazard cascades downstream from moraine-dammed lakes commonly must specify linkages between models of discrete processes such as wave overtopping, dam breaching, erosion, and downstream floods or debris flows. Such linkages can be rather arbitrary and can detract from the ability to accurately conserve mass and momentum during complex sequences of events. Here we describe an alternative methodology in which we use high-resolution lidar topography and 2-D, two-phase conservation laws to seamlessly simulate all stages of a hazard-cascade that culminates in a debris flow. Our simulations employ our depth-integrated numerical model D-Claw to evaluate hazards from prospective breaching of a moraine dam that impounds Carver Lake on the eastern flank of South Sister volcano in central Oregon, USA. We simulate a "worst-case scenario" sequence of events that begins with a hypothetical 1.6 million m^3 landslide that originates near the summit of South Sister and enters Carver Lake. Wave generation and displacement of lake water then leads to dam overtopping, breach erosion, and a downstream debris flow that funnels into Whychus Creek and eventually reaches the community of Sisters, Oregon, about 20 km away. Notably, our simulations predict that much of the debris is directed away from Sisters as a result of natural avulsion and flow diversion that occurs near the head of a low-gradient alluvial fan upstream from Sisters. Consequently, predicted hazards to downtown Sisters are less severe than those predicted by 1-D shallow-water simulations of a Carver Lake dam breach that were performed in the 1980s.

Keywords: debris-flow modeling; lake-outburst floods; two-phase modeling; Carver Lake; South Sister volcano.

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1. Introduction

D-Claw is a software package that we developed primarily for simulating landslides and debris flows, but it can also be applied to a wider class of problems that involve water bodies as well as grain-fluid mixtures. The depth-averaged model describes the temporal and spatial evolution of flow thickness, velocity, solid and fluid volume fractions, and basal pore-fluid pressure (Iverson and George, 2014; George and Iverson, 2014). However, in the limit of vanishing solid volume fraction, D-Claw's model equations reduce to the shallow water equations, allowing the simulation of water waves or overland flooding in a way similar to that of models developed specifically for those applications (*e.g.,* Berger et al., 2011). We have recently exploited this property and used D-Claw to simulate cascading natural hazards, such as tsunamis generated by subaerial landslides (George et al., 2017), glacial lake-outburst floods, and overland floods that entrain debris. For these applications we can seamlessly employ D-Claw without needing to specify interaction terms or couple disparate models and software. This approach ensures accurate conservation of mass and momentum throughout the cascade of processes.

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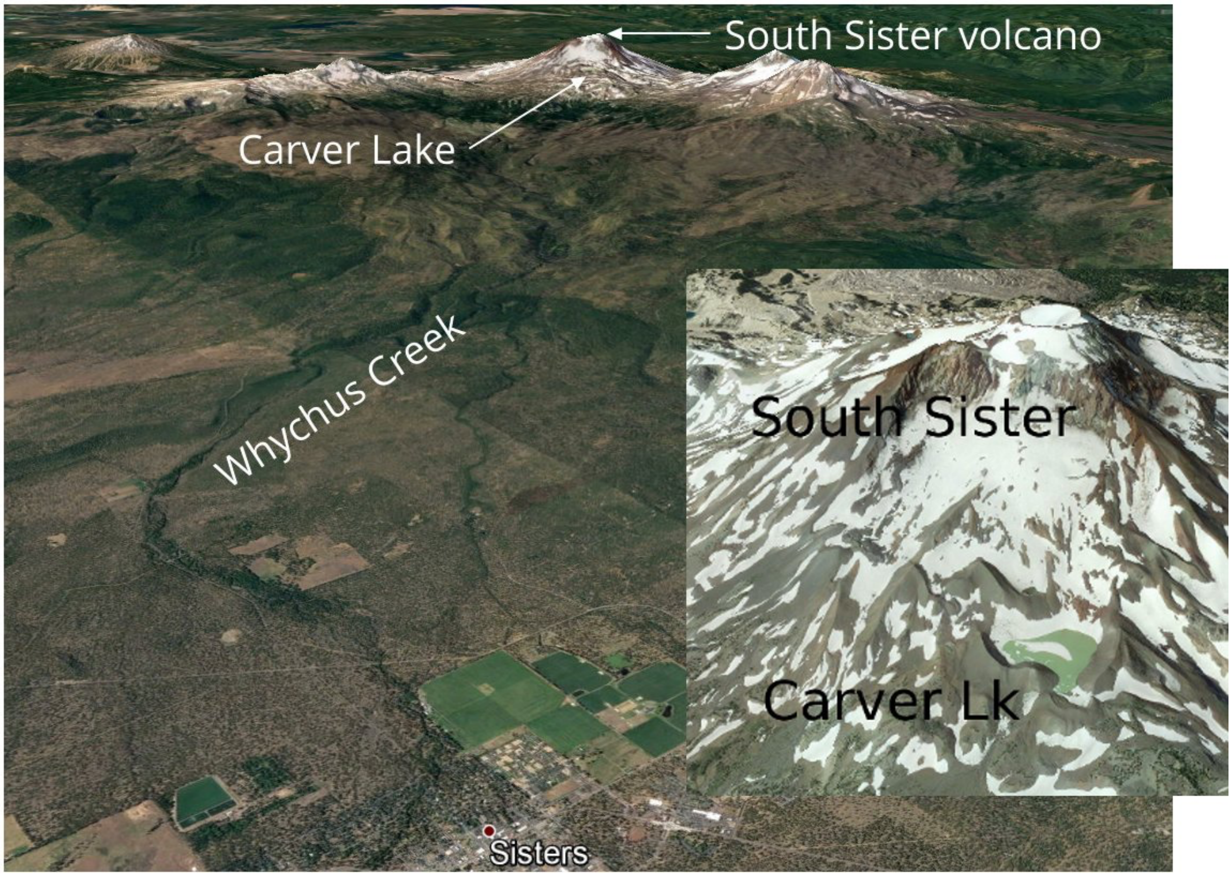
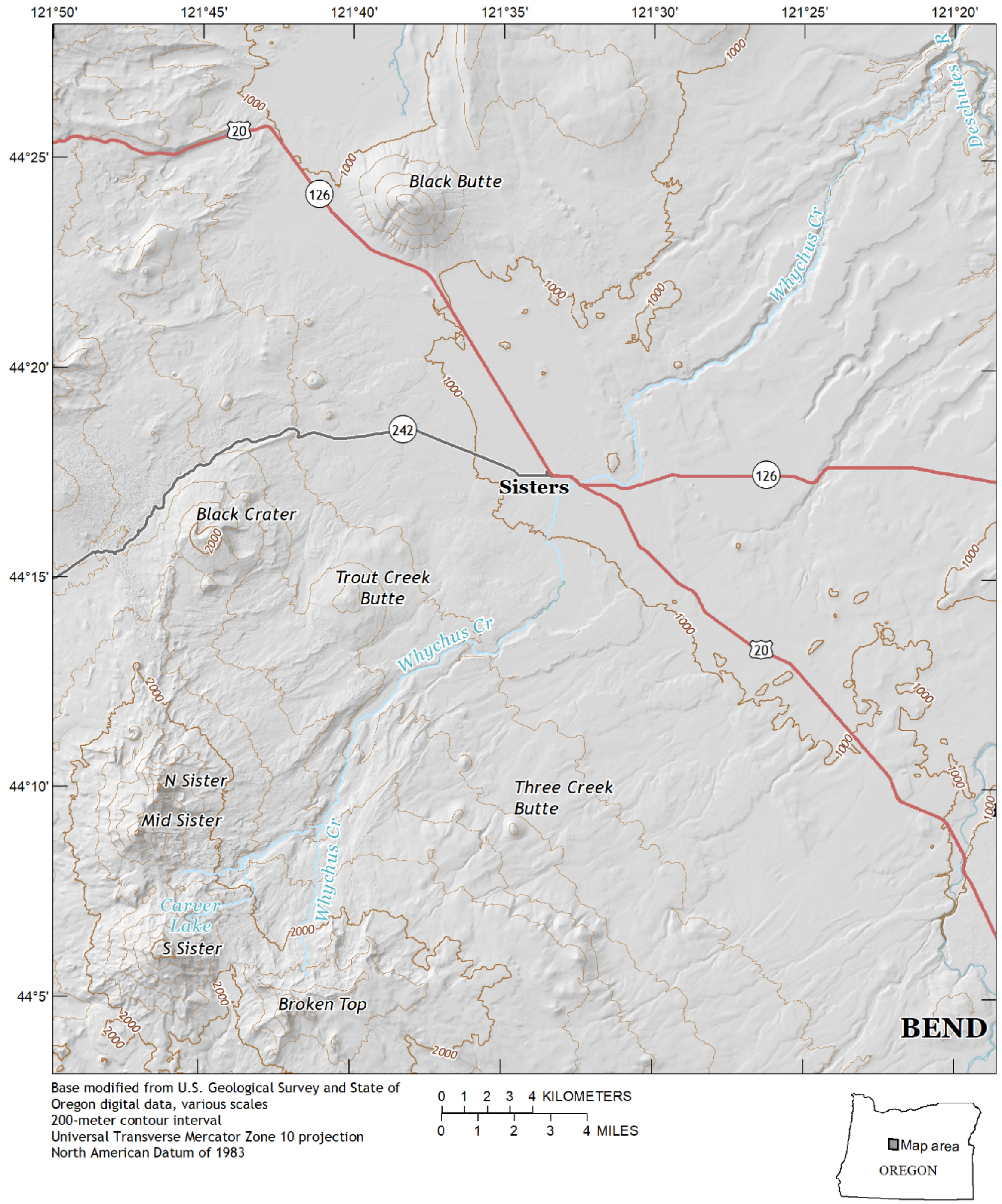


Figure 1. Southwest-looking Google Earth imagery showing the location of the community of Sisters, Oregon, in relation to Carver Lake and South Sister volcano.

In a recent study, we used D-Claw to model a hypothetical outburst flood from a moraine-dammed lake on the east side of South Sister volcano near the town of Sisters, Oregon, USA. The hypothetical landslide begins near the summit of South Sister and enters Carver Lake, where it generates large waves that overtop the moraine dam. Because D-Claw can model the erosion and entrainment of basal sediment, the subsequent dam breaching process occurs spontaneously, leading to lake drainage and downslope floods and debris flows. Owing to spreading and avulsion of the modeled flow in a system of distributary channels on the alluvial fan upstream from Sisters, the predicted hazard to the community is less severe than was predicted by 1-D shallow-water computations performed in the 1980s (Laenen et al., 1987), as the 1-D modeling does not make possible the direct modeling of stream bifurcation, but rather requires the primary flood channel to be chosen *a priori*.

2. Hazards Downstream from Carver Lake, Oregon

Carver Lake is a moraine-dammed lake on the eastern flank of South Sister volcano in central Oregon, USA (Figures 1 and 2). The lake sits approximately 20 km upstream from the community of Sisters, Oregon, located in the valley below. The outlet channel of Carver Lake is a small tributary of Whychus Creek, which flows through downtown Sisters.



Base modified from U.S. Geological Survey and State of Oregon digital data, various scales
200-meter contour interval
Universal Transverse Mercator Zone 10 projection
North American Datum of 1983

Figure 2. Map showing the location of Carver Lake (near southwest corner) and Sisters, Oregon.

In the 1980s, concern was raised regarding the flooding risk posed to the Sisters community, should a moraine-dam failure lead to an outburst flood from Carver Lake. Modeling conducted at the time utilized 1D shallow-water equations and suggested that, in the event of complete lake drainage, the flooding hazard could be substantial (Laenen et al., 1987). Because of recent advances in flood and debris-flow modeling capabilities, there has been interest by community members to reassess this hazard with more sophisticated methods.

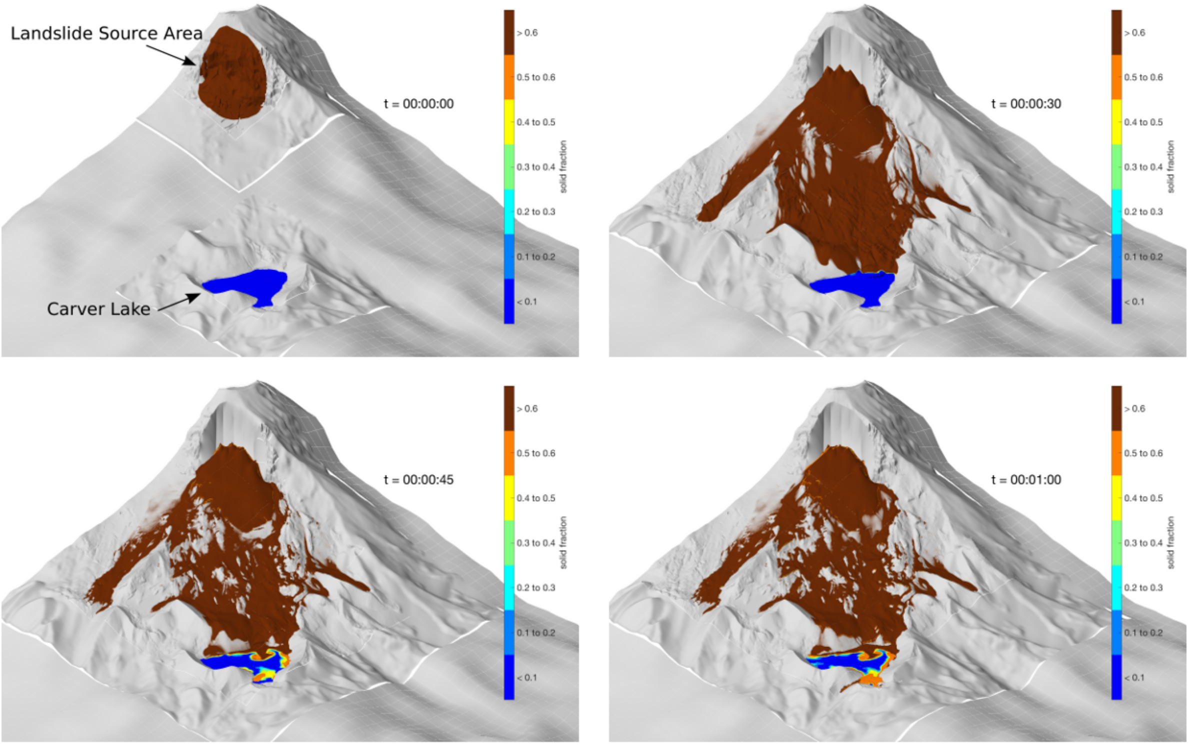


Figure 3. West-looking oblique perspective of the failure and evolution of the simulated landslide mass which inundates Carver Lake and generates waves that overtop the moraine dam. The wave action at the dam begins to erode channel material. Shading indicates the solid volume fraction, *m,* which varies from 0 (pure water) to ~ 0.6 (dense granular-fluid mixture). The area depicted is ~ 3 x 3 km^2.

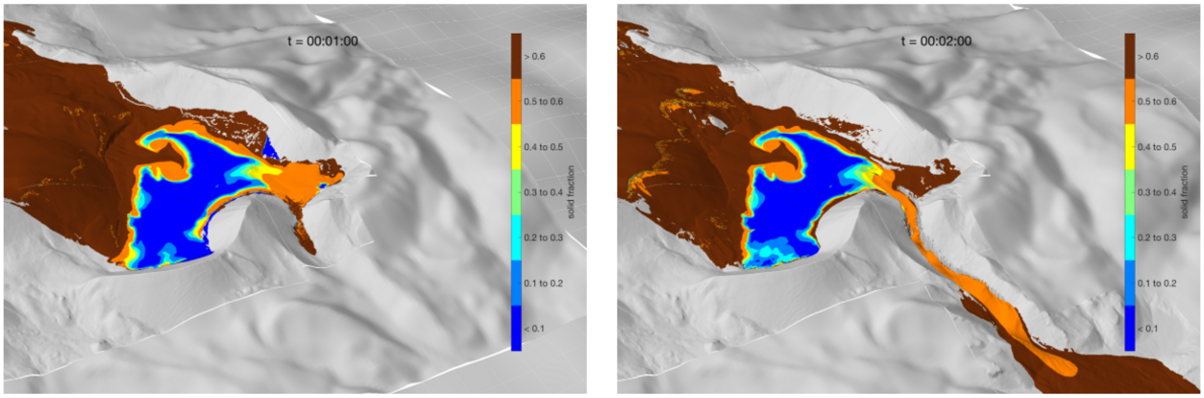


Figure 4. North-looking oblique perspective of wave generation, overtopping and erosion of the moraine dam that leads to a downstream debris flow. Shading indicates the solid volume fraction, *m,* which varies from 0 (pure water) to ~ 0.6 (dense granular-fluid mixture). The evolving values of *m* reveal the mixing and nature of the downstream flow. Area shown is ~ 1.5 x 1.5 km^2 .

There is consensus among geologists and engineers who have visited Carver Lake (*e.g.,* Laenen et al.,1987; O'Connor et al., 2001) that the moraine dam appears stable to spontaneous failure, and that a failure would most likely require overtopping waves generated by a landslide entering the lake. We therefore used D-Claw to simulate scenarios in which a landslide originates on the slopes of South Sister above Carver Lake. All subsequent processes (*e.g.,* wave generation, dam overtopping, erosion, downstream flooding and debris flows) were simulated seamlessly. That is, dam failure and flooding were not specified by the model set-up. Assumptions only about the landslide size and location and the erodibility of the dam material were explicitly prescribed.

3. Modeling

3.1 Model Set-Up

D-Claw simulations were performed on a large domain (approximately 50 km by 50 km), which included the summit of South Sister in the southwest corner and extended northward beyond the community of Sisters. High-resolution lidar topography (approximately 1 m) from 2017 was available throughout the domain, but required some manual modifications due to recent channel alterations near Sisters, which occurred as part of an ecological restoration project. Due to D-Claw's use of adaptive mesh refinement (AMR), model resolution varied dynamically as flows evolved, but 1 m resolution was retained in the valley surrounding Sisters.

A hypothetical landslide source geometry encompassing 1.6 million cubic meters of material was constructed by first creating transects running longitudinally along the length of the hypothetical basal failure surface, in the form of logarithmic spirals, near the summit of South Sister volcano and extending downslope toward Carver Lake. A continuous basal surface was then constructed by interpolating the transects with a triangulated network. The transects were constructed such that the failure surface had prescribed scarp and toe inclination angles. The specific geometry was chosen with the goal of creating a large enough landslide to significantly displace the water in Carver Lake, yet conform reasonably to the local topography. Computations were initialized in D-Claw with a solid volume fraction, m=0.62, within the landslide source area and throughout the rest of the computational domain, except for within Carver Lake (Figure 3).

Our DEM was modified to include Carver Lake bathymetry collected in the field in 2016. The D-Claw simulation was initialized with pure water ($m = 0$) above the bathymetry of Carver Lake, and below a horizontal lake surface with an elevation determined from field surveys. This resulted in a lake volume of 1.4 million cubic meters.

A region beginning near the upstream face of the moraine dam and extending downstream from the lake outlet was initialized with potentially erodible material occupying depths approximately 20 meters below the current DEM topography, and extending for approximately 300 meters downstream along the drainage channel. The erodible material was assumed to be a saturated granular-fluid mixture with the same material properties as the surrounding material, but was subject to entrainment under the physical constraints identified by Iverson and Ouyang, 2015, where the basal stress jump and a tunable coefficient is used to define the entrainment rate. The channel geometry was chosen based on current topography and slope gradients.

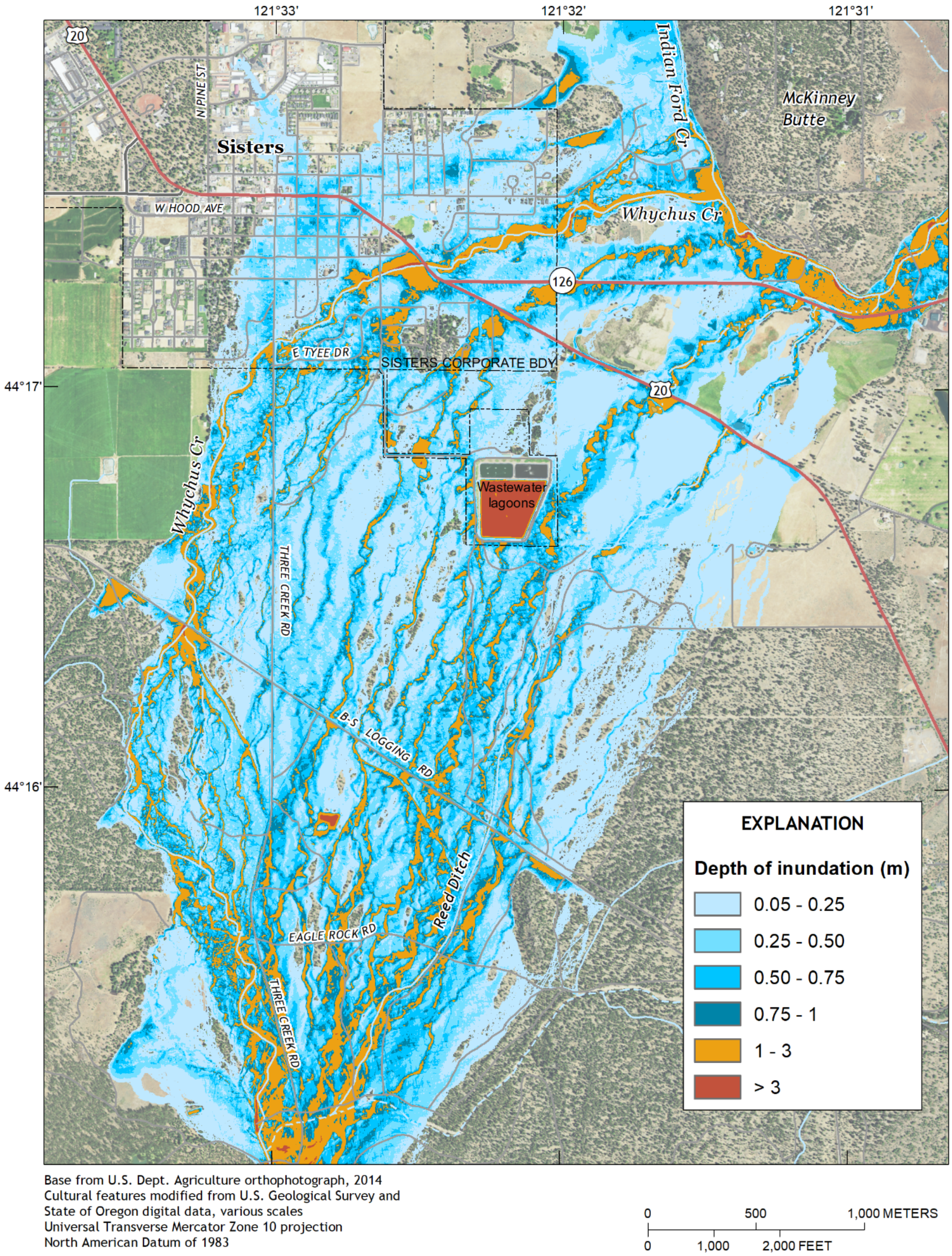
3.2 Model results

At the start of the D-Claw simulation, the pore-fluid pressure acting on the base of the landslide mass was manually raised until failure commenced locally at the weakest location. The manual manipulation then ceased and D-Claw's evolution equations dictated the failure process and coupled evolution of pore pressure.

After failure commenced, the landslide material became nearly liquefied and accelerated downslope, eventually inundating Carver Lake (Figure 3). The model equations led to mixing of material and generation of impulse waves in the lake. The waves eventually overtopped the crest of the dam, eroding bed material in the process, leading to channel excavation. The positive feedback loop of dam and channel erosion led to further flooding and lake drainage. After approximately 5 minutes simulated time the lake evacuation stabilized, leading to a mixture of landslide material and fluid stranded in the lake bed (Figure 3). The flow downstream of the dam had the characteristics of a debris flow, with $m = 0.5 - 0.6$ (Figure 4).

The D-Claw simulation continued to resolve the downstream flood and debris flow as it descended the lower flanks of South Sister volcano. By utilizing AMR, grid efficiency was greatly enhanced by only resolving parts of the domain with active flow (*c.f.* (Berger et al., 2011)).

The debris flows and flooding were primarily confined to the Wychus Creek drainage for an approximately 15 km reach downstream of Carver Lake, where the creek is deeply incised for much of its path.



Base from U.S. Dept. Agriculture orthophotograph, 2014
Cultural features modified from U.S. Geological Survey and
State of Oregon digital data, various scales
Universal Transverse Mercator Zone 10 projection
North American Datum of 1983

Figure 5. D-Claw results showing the flood and debris-flow inundation in the alluvial fan surrounding Sisters. Shading indicates the maximum depth observed at any location for the duration of the simulation.

Several kilometers upstream of the community of Sisters, Whychus Creek debouches onto an alluvial fan with low relief and a system of (now dry) distributary channels. When the modeled flow reached this point after approximately 1 hour, it immediately overtopped the low banks of the main branch of Whychus Creek, spreading into the distributory channels. The flow continued to spread widely across the alluvial fan, eventually inundating Sisters (Figure 5). However, due to the spreading, the depth of the flow in the main channel was reduced significantly, presumably lessening the flood risk posed to the more densely populated area of Sisters adjacent to the main channel. The results contrasted with early 1-D simulations performed in the 1980's, which assumed that most of the flow was confined to the channel.

4. Conclusions

Dam-break outburst floods and other phenomena that involve grain-fluid mixtures (*e.g.*, landslides, debris flows, dam breaches and bed-material entrainment) interacting with bodies of water, pose modeling challenges due to the multi-physics nature of the cascading hazards. Coupling disparate models together is less than desirable, due to implementation difficulties and model inaccuracy from *ad hoc*, non-conservative, coupling assumptions.

We used D-Claw to seamlessly model a hypothetical landslide and the resulting cascade of lake inundation, wave generation, dam overtopping, breach growth and downstream debris flow. The modeling approach requires only initial conditions and material parameters for the landslide material, water, and erodible bed material with no explicitly specified coupling assumptions. Obtaining high-resolution results with such simulations also requires use of high-resolution digital topographic data, such as the lidar data we utilized in this study.

Compared to earlier studies employing 1-D equations and coarse topography, our modeling suggests a strikingly different result for our test case involving inundation near Sisters, Oregon. Owing in part to the use of 2-D equations as well as high-resolution lidar topography, our results suggest that flow avulsion and diversion on the alluvial fan surrounding Sisters would lead to a less severe flood hazard to the community.

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