Quantification of Recent Movement, Volume, Ablation, and Meltwater Contributions of the Dana Glacier, Sierra Nevada

A cumulative report on my four years of scientific research at the Dana Glacier, Sierra Nevada, California.

Ellery McQuilkin

January 2022

Introduction

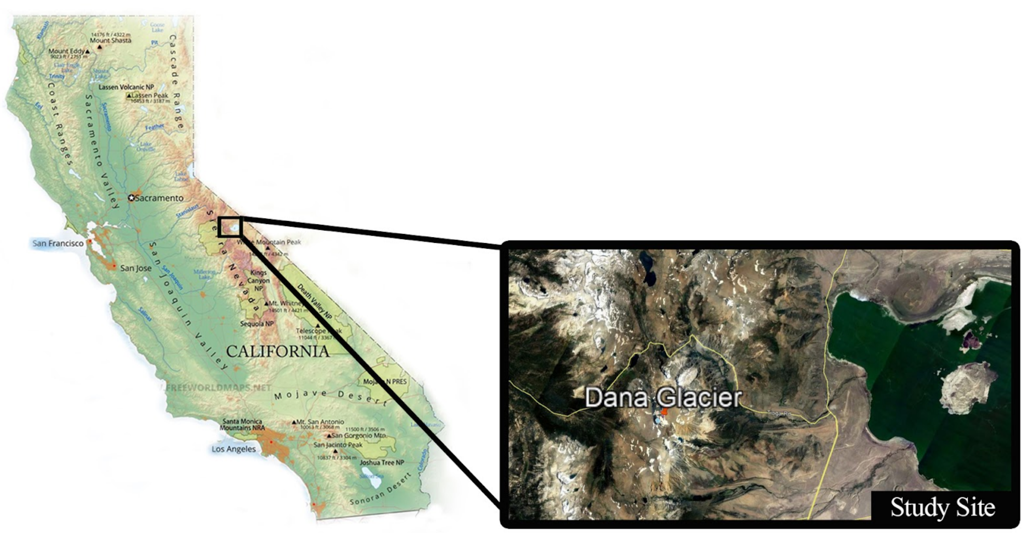
Several small glaciers, formed during the Matthes Glaciation (Raub, 2006), currently occupy high elevation cirques in the Sierra Nevada, California. The total ice volume of these glaciers is rapidly decreasing and previously documented glaciers have melted away entirely (Basagic, 2011). Glaciers across the world are rapidly losing volume as the impacts of anthropogenic climate change worsen. In the Sierra, these effects are particularly noticeable due to the small size of these glaciers and their subsequent sensitivity to the climate (Phillips, 1996).

Through my detailed quantification of the present state of the Dana Glacier (Fig. 1), one of these diminishing cirque glaciers, we can gain insight into the future of glaciers in the Sierra and better understand the impacts of climate change upon the Dana Glacier.

Figure 1: The Dana Glacier, elevation 3500 m, slope 30º, sits underneath Mt. Dana and is shaded by the tall headwall.

Background

Glaciers are formed as accumulated snow compacts into firn and then compacts further into ice. When a significant amount of ice has been accumulated the “gravity induced stress” becomes large enough for the ice mass to flow downhill, making it a glacier (Guyton, 2001). Glaciers form in environments at high altitudes or high latitudes. Mountain glaciers initially form within cirques, which are shaded basins beneath tall peaks. Snow accumulates more quickly and melts at decreased rates within cirques, so in these areas glaciers can reach a thickness great enough to result in flow and expansion into valley glaciers (Hill, 2006). Over the last 120 years, glaciers in the Sierra have receded back into these cirques where the effects of increased melting are buffered by shade and avalanching that contributes to accumulation (Sanders, 2010). Current Sierra glaciers were formed in the Little Ice Age (1250-1900), but occupy cirques that were carved out in the Pleistocene period about 2 million years ago (Raub, 2006).



The Sierra Nevada is a high elevation alpine environment with cold winters and warm summers. Moisture from the Pacific is pushed towards the mountain range and deposited on the West slopes and high elevation peaks. The mountain range is 640 km long and consists of many high elevation peaks that are home to cirque glaciers (Basagic, 2011). The high altitude (2763m -

4267m) northern facing basins, and cirque buffering effects are the primary reason that glaciers still exist in the Sierra today.

Many cirque glaciers still exist in the Sierra. Since their formation in the Little Ice Age approximately 700 years ago, these glaciers have expanded and retreated in natural cycles. The last glacial maximum occurred in the early 1900s; since then they've receded substantially (Basagic, 2011). Several studies have estimated the approximate number of glaciers in the Sierra, all averaging at about 100 true glaciers (Basagic, 2011). While these studies are still fairly recent (10-20 years ago), Sierra glaciers are melting at such a rate that by now, actual numbers are likely much lower. Current estimates place the number of true glaciers at around 50 (Fountain, 2021).

Sierra glaciers are remote and can be difficult to access, so few extensive studies have been performed on these glaciers. In 1871, John Muir identified the ice mass underneath Black Mountain to be a glacier, and soon determined that Lyell and Maclure were also glaciers. These were the first reported documentation of glaciers in the Sierra--it should be noted that this does not account for Indigenous records that exist in oral history. In 1883 Israel Russell conducted repeat photography (Fig. 2, Fig. 3) and mapping of several glaciers in the Sierra (Basagic, 2011). These photo points show the glaciers at approximately their most recent maximum, providing a valuable comparison point for the present.

Dana Glacier 1883 - ric046 photo station (Israel Russell)

Dana Glacier 2021 - ric046 photo station (2021 E. McQuilkin expedition to the Dana Glacier, Rachel Hallnan)

Figure 2: Dana Glacier shrinkage over the last 138 years from ric046 photo station.

Dana Glacier 1883 - ric049 station (Israel Russell)

Dana Glacier 2021 - ric049 station (2021 E. McQuilkin expedition to the Dana Glacier, Rachel Hallnan)

Figure 3: Dana Glacier shrinkage over the last 138 years from ric049 photo station.

From 1930 - 1975 the National Park Service conducted yearly evaluation of the Lyell, Maclure, Dana, Conness, and occasionally Kuna glaciers. Photo points were established and several measurement points for recording surface area ice loss were created along the perimeter of these glaciers. The overall trend of these measurements shows loss (NPS, 1933-1975). The Palisade, Lyell, Maclure, and Conness glaciers have all undergone more thorough studies, primarily through the aforementioned NPS studies, making them interesting reference points to the Dana Glacier.

The Dana Glacier has been included in several overview studies looking at Sierra glaciers in general. The historical NPS reports are relatively detailed field studies of the Dana Glacier. They measured ice loss and established repeat photo points that also demonstrate large shrinkage. Even in the 1930's the Dana Glacier was reported as appearing to be a "remnant" (NPS, 1933-1975) while still having many glacial features like a large ice cave, crevasses, and large hummocks. Since the NPS reports, no research, other than repeat photography and occasional perimeter mapping, has occurred until my 2019 - 2021 studies.

Dana Glacier Velocity Study: 2019 - 2020

The defining characteristic of a glacier is movement. There are two aspects to glacial movement: basal slip and deformation. The upper layers of the glacier move more quickly than lower layers in a process called deformation. Deformation is usually largest at the center of the glacier because the ice is the thickest there (Sharp, 1992). Basal slip occurs primarily during the summer when melt water lubricates bedrock and the entire ice mass slides down slope (Sharp, 1992). Basal slip is a larger driver of movement on warm glaciers because there is generally more melting in the summer which enhances basal slip (Sharp, 1992). As glaciers move, they pluck rocks from bedrock and pick up loose debris. When they retreat, the debris is left behind in lateral and terminal moraines. These moraines serve as a primary indicator for past glacial advances (Hill, 2006).

Measuring the movement of glaciers can be done through several methods--satellite imagery and mathematical formulas are commonly used on large glaciers, but are not as useful on small glaciers (Fountain, 2021). To study movement of the Dana Glacier I designed a study and assembled a team to gather direct field measurements of movement.

To determine if measurable movement is present on the Dana Glacier I lead a research team to the Dana Glacier in early October 2020. My research team used stakes as markers and surveyed their change in position over periods of time. In early October, we placed 3 stakes, composed of four 1m sections of PVC, on the Dana Glacier, each drilled 4m into ice with an ice auger, and surveyed them using a laser range finder and a high precision GPS. The three stakes were placed at generally the same elevation spanning across the width of the glacier. 55 days later we returned and

re-surveyed the stake's locations. The stakes were all frozen into the glacier and could not be retrieved. We returned a year later and resurveyed the poles and removed them. Stake 2 had melted out and could not be resurveyed.

The laser rangefinder produced the most precise measurements, and since movement was small (for the first period), the laser range finder measurements were used over the GPS measurements, which did not show movement outside the range of error. The laser range finder gives horizontal, vertical, and slope measurements. The general standard is to use horizontal numbers to evaluate movement. These numbers for the Dana Glacier show:

	Horizontal movement (m) August - October	Horizontal movement (m) August 2020 - August 2021
Stake 1	0.4 +/- 0.5	3.2 +/- 0.5
Stake 2	0.6 +/- 0.5	N/A +/- 0.5
Stake 3	0.2 +/- 0.5	3.2 +/- 0.5

The horizontal numbers only evaluate movement of ice towards the base point on a 2D plane, but on a glacier as steep as the Dana, it is logical to assume that a considerable amount of the movement is downslope. Downslope measurements also have a lower rate of error.

	Downslope movement (m) August - October	Downslope movement (m) August 2020 - August 2021
Stake 1	1.1 +/- 0.1	4.2 +/- 0.1
Stake 2	1.2 +/- 0.1	N/A +/- 0.1
Stake 3	1.2 +/- 0.1	4.3 +/- 0.1

When these downslope numbers are considered, discernable movement did occur over the 55 day period from August to October. This is likely the time of peak movement due to the increased meltwater running underneath the glacier which increases basal slip (Sharp 1992). Using downslope numbers we can determine that summer movement over a 55 day period (15% of the year) makes up 26% of the movement for the year. When only considering horizontal movement numbers, the summer melt rate cannot be so precisely assumed, but clear movement over the span of the year is identifiable. The rate of average movement per day at the Dana Glacier is 0.88cm for horizontal movement and 1.12cm for downslope movement.

No past field movement studies have been conducted on the Dana Glacier, so there is not a past rate to which I can compare these numbers. However, the nearby Lyell and Maclure Glaciers in Yosemite National Park, which have a similar climate and local topography, can be a valuable comparison point. The Lyell Glacier, which has a volume about 4 times that of the Dana Glacier, has stagnated (Stock, 2012), while the Dana Glacier continues to move at approximately 4 m per year. This indicates that the steep slope of the Dana Glacier is prolonging movement.

Dana Glacier Volume Study: 2020 - 2021

Evaluating the volume of cirque glaciers is a difficult process, as there is no way to directly observe the bottom of the glacier. Many methods, such as remote surveying, satellite imagery analysis, and mathematical formulas for evaluating volume, are designed for larger glaciers and were likely to be ineffective on the Dana Glacier (Stock, 2021). The final procedure I used on the Dana Glacier combined the use of direct field measurements of depth with 3D modeling. To obtain the direct field measurements, we used a Hueke steam drill (Fig. 5), a piece of specialized ice equipment that uses pressurized steam to melt small diameter holes through ice.

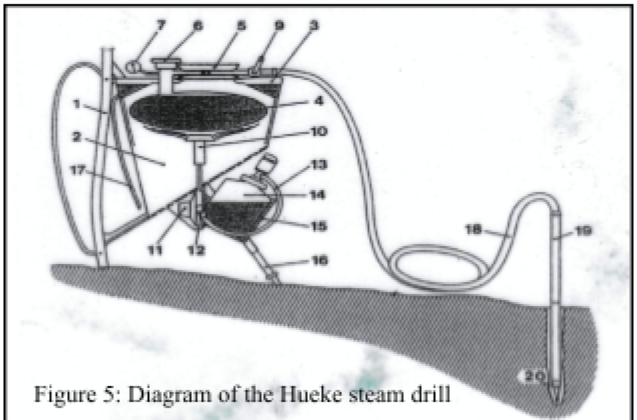
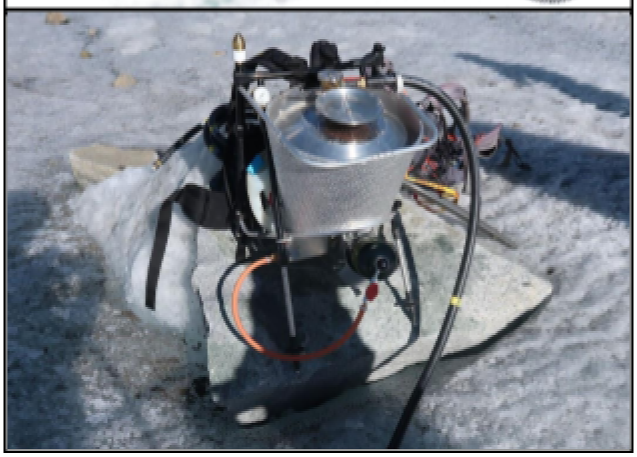


Figure 5: Diagram of the Hueke steam drill



In October 2020, I led a research team expedition to the Dana Glacier. We hiked four miles to the glacier, established a base camp and then continued on the glacier itself at 3500 m elevation. On the first day we drilled three holes using the steam drill and we drilled two more successfully the following day. We stopped at photo points on the path to the glacier (Fig. 6).


Dana Glacier 1883 (Israel Russell)


Dana Glacier 2020 (E. McQuilkin 2020 expedition, Geoff McQuilkin)

Figure 6: Dana Glacier, Glacier Lake photo point. Base camp was at this location.

We used the steam drill to melt 5 holes into the Dana Glacier over a period of two days. We drilled primarily in areas of the glacier where it was likely we could reach bedrock with the 13.5 meter maximum of the steam drill. The drilling locations were spread across the glacier in order to gain information about depths across the entire glacier (Fig. 9). In some locations, depths were greater than 13.5 m so bedrock was not reached, however, this also provided useful insight into glacial thickness. The steam drill also had some technical issues, as the gas line froze up in the below freezing temperatures. This considerably slowed down the drilling process and meant the maximum drilling depth could not be reached at every location.

Figure 7: Using the steam drill and shaded, icy field conditions.

This trip occurred in mid-October when the glacier is typically covered in shade for almost the entire day. Temperatures remained around freezing and conditions were very icy, meaning movement around the glacier required belay lines in addition to the use of crampons and ice axes (Fig. 7)

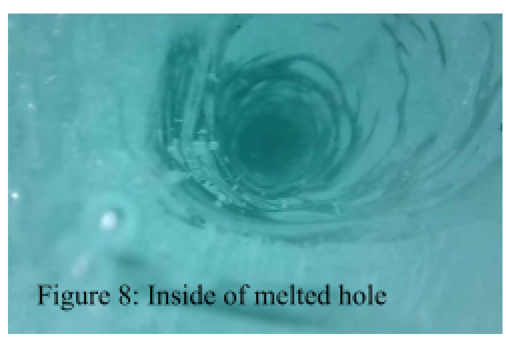
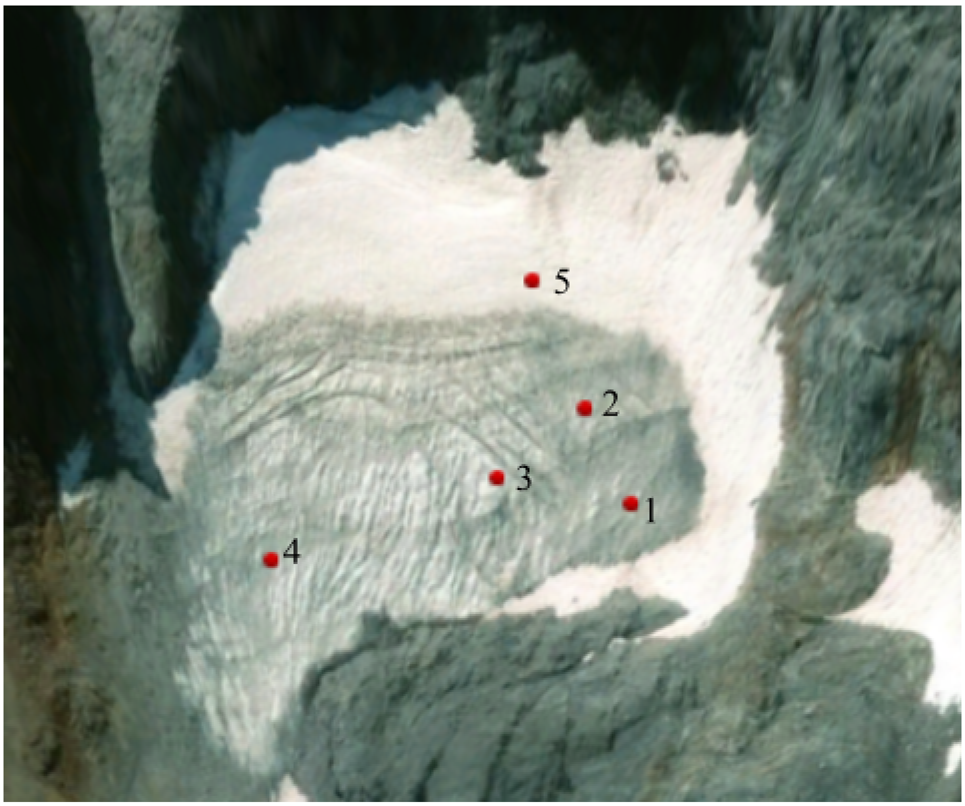


Figure 8: Inside of melted hole

The cold conditions also meant that there was minimal melt water available so we carried liters of water to each location to use in the steam drill. Once the steam drill was running it took 45 minutes to two hours to complete drilling at each location. The amount of time at each location was heavily dependent on how well the gas line was functioning. When drilling it was clear that bedrock had been reached as the steam drill hose stopped moving and the vibrations changed.

We also dropped a borehole camera down the hole to try to see the bedrock, or the bottom of the hole. These images were generally not very helpful as the camera element had limited capability to withstand cold temperatures by the time it reached the bottom of the hole. However it did yield impressive photos of the ice in the first meter of the hole (Fig.8).

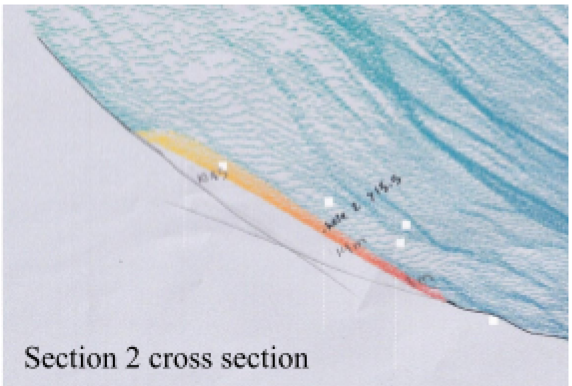


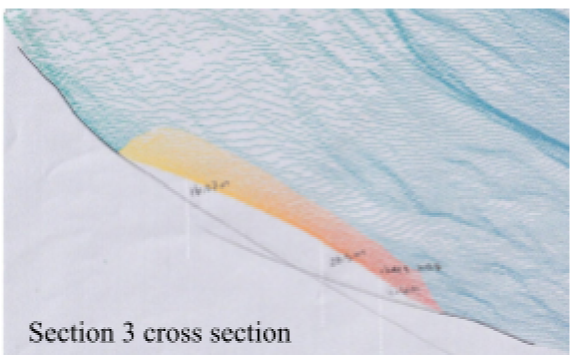
	Depth (meters)	Data Type	UTM coordinates (11S)
Hole 1	3.0	Bedrock depth	304916 4197264
Hole 2	13.5	Minimum thickness	304912 4197212
Hole 3	10.5	Minimum thickness	304962 4197220
Hole 4	9.5	Minimum thickness	305062 4197197
Hole 5	13.0	Minimum thickness	304909 4197142

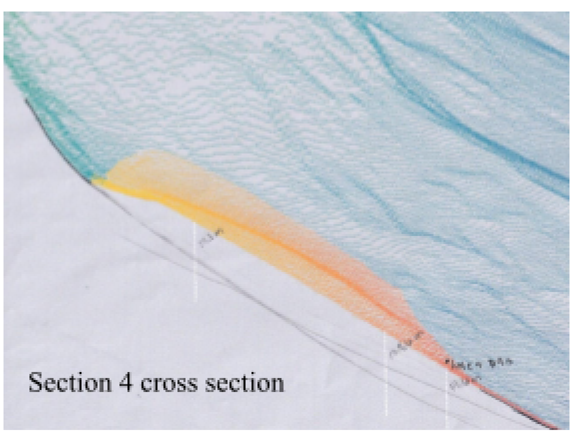
Figure 9: Location of drilled holes and their depths.

3D Modeling Methods

To supplement the data obtained through direct depth measurements from the field, I created 3D models using ArcGIS Pro and Cloud Compare softwares. Using Cloud Compare, I created digital cross sections of the glacier and the surrounding terrain (Fig. 10). In each cross section, there is a clear line one can draw that connects the bedrock edges, effectively making a projection of the shape of the bottom of the glacier. I created five cross sections of the glacier and drew in the logical bedrock line for each of these cross sections. The cross sections were created at the locations in which we had drilled, so the depth information from the drill was used to draw the most reasonable bedrock lines. Three depth points were derived from each bedrock line, these included lengthening the minimum depth points obtained with the steam drill.







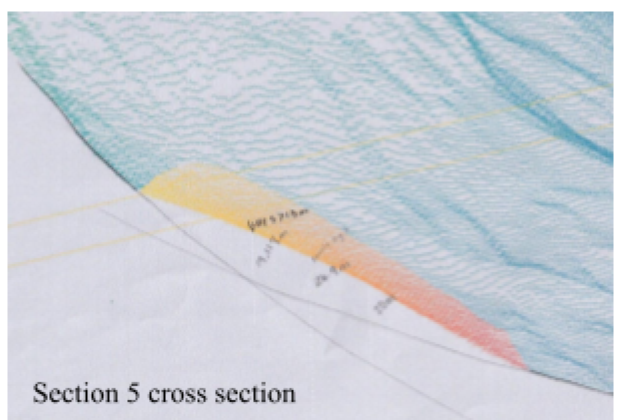
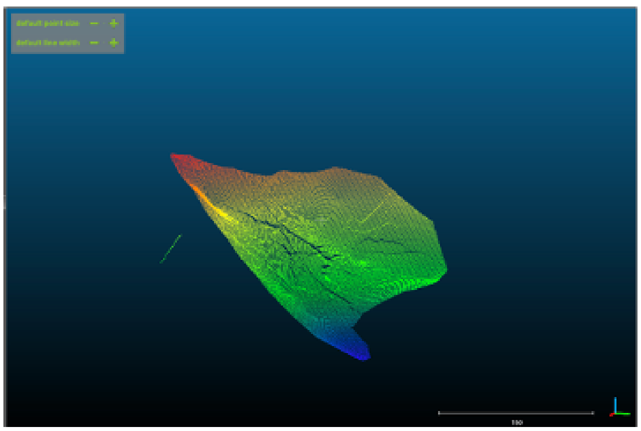
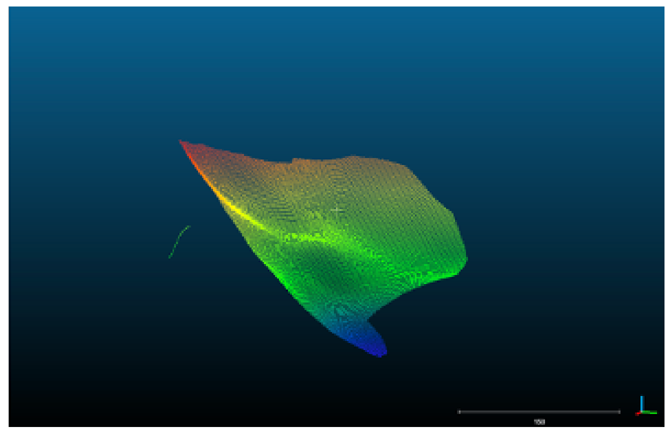


Figure 10:
Cross sections of glacier, created in Cloud Compare using lidar data. Blue represents the bedrock; orange is the ice surface. I drew in the logical bedrock lines.

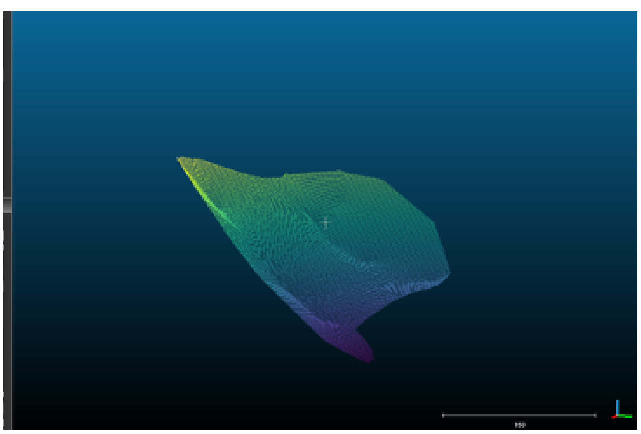
With 15 depth points in the center of the glacier and 20 defining the margin of the glacier, I used ArcGIS Pro to interpolate bedrock surfaces. I used Spline, Kriging, Natural Neighbor, and IDW interpolation tools to construct potential bedrock surfaces (Fig. 11). Using visualization tools from Cloud Compare and experience from the field, I determined the Krigging bedrock surface was the most reasonable. It lacked the surface irregularities caused by the IDW tool and the exaggerated depth created with the Spline tool.



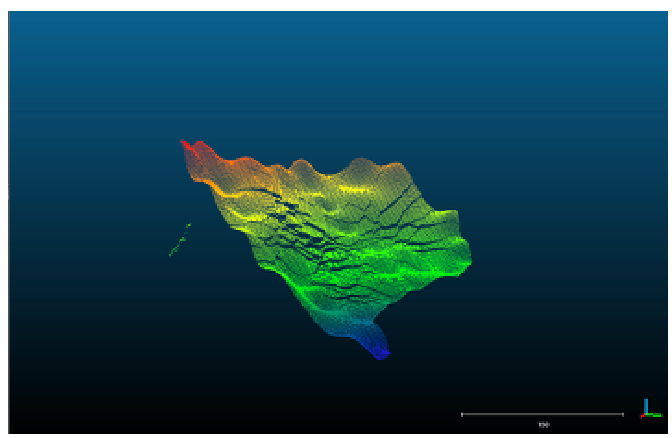
Krigging bedrock surface
Volume: 590,000 cubic meters



Spline bedrock surface
Volume: 644,600 cubic meters



Natural Neighbor bedrock surface
Volume: 558,000 cubic meters



IDW bedrock surface - note surface irregularities
561,000 cubic meters

Figure 11: The four modeled bedrock surfaces.

Results

I combined my modeled bedrock surface with the 3-meter lidar data ice surface to create a three dimensional model of the Dana Glacier in a 3 m grid (Fig. 12).

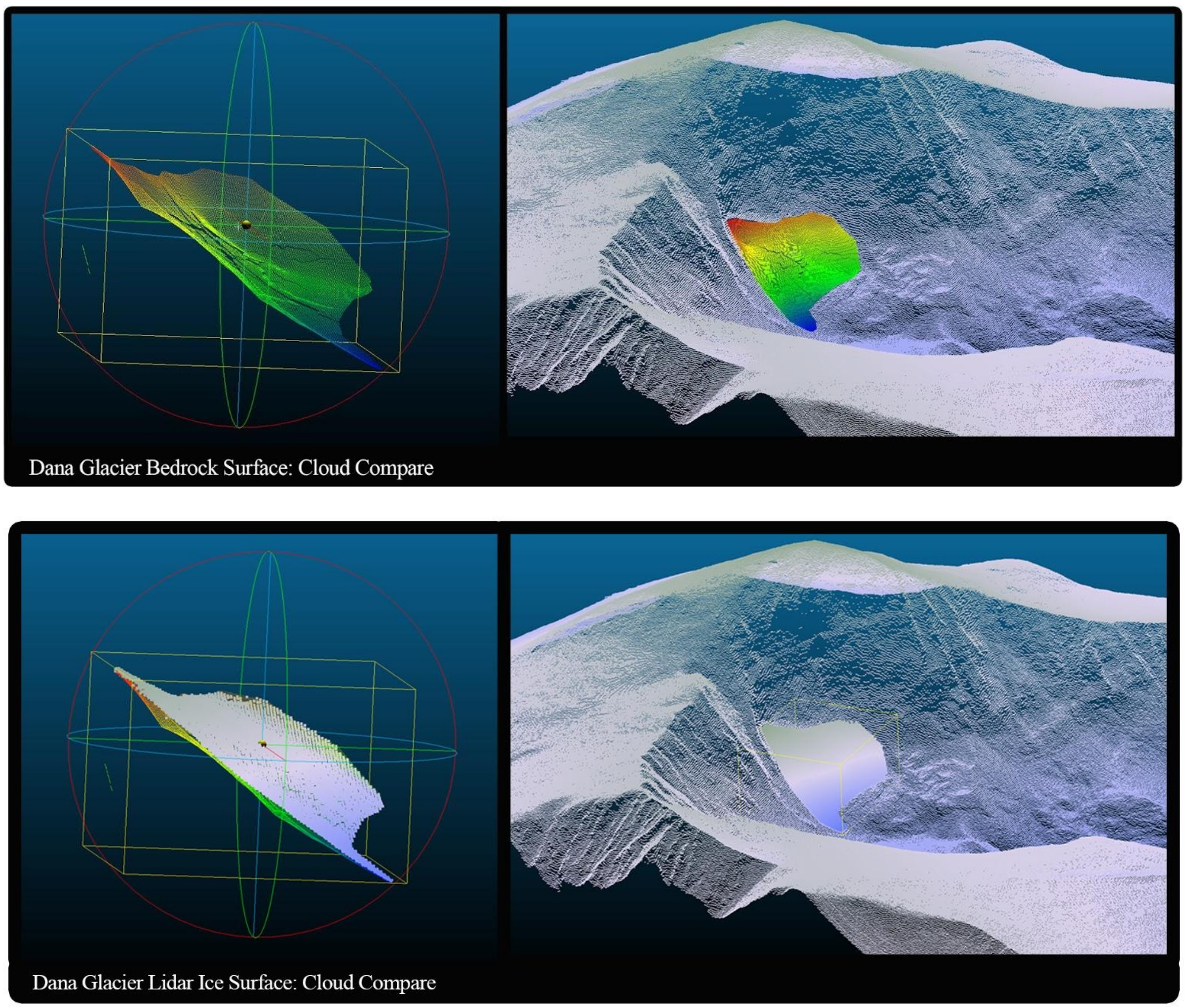


Figure 12: Three-dimensional model of the Dana Glacier.

My model of the glacier reported depth for each of the 8000 cells in the model. I analyzed the distribution of glacier depth for each cell provided by this model (Fig. 13).

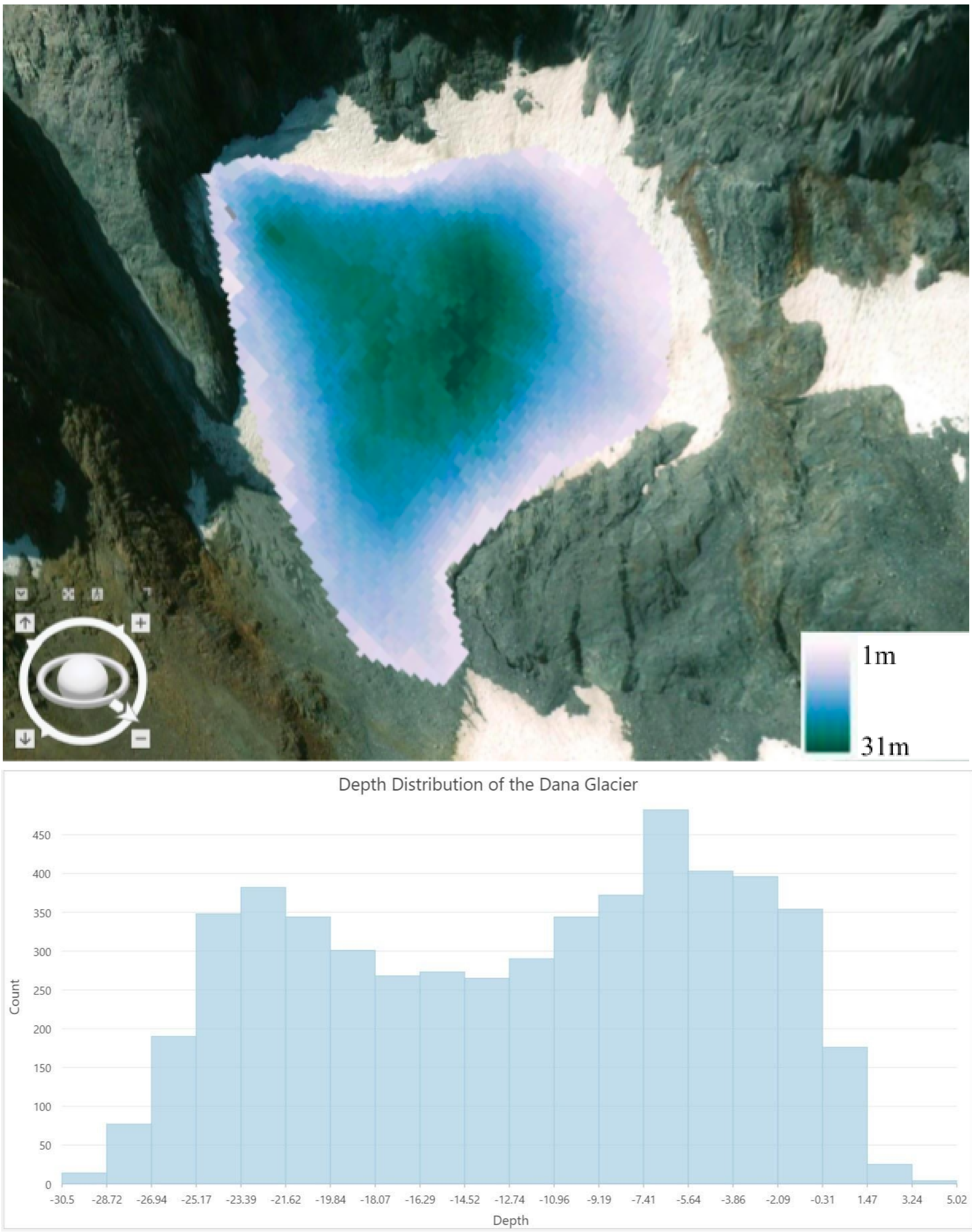


Figure 13: Depth distribution map and chart of the Dana Glacier. Darker colors represent larger depths.

I determined that the average thickness of the Dana Glacier is 12 meters. 50% of the glacier is under 13 m thick, and the deepest part of the glacier is 31 m thick. To determine total volume, I used GIS to add the volumes of each of the 8000 cells together and project a total volume of 5.96×10^5 cubic meters. For reference, this is approximately enough ice to fill the Rose Bowl. As a reasonability check, I calculated volume using the three other bedrock surfaces and all were within 10% of the chosen model.

This is a very small total volume and average thickness for a glacier. For comparison, the Lyell Glacier has an estimated volume of 2.3×10^6 m^3 ± 1×10^6 m^3 and the Maclure Glacier has an estimated volume of 2.6×10^6 m^3 ± 7×10^5 m^3 (Nikita Avedievitch, 2022). The Lyell Glacier has a volume about 4 times that of the Dana Glacier, yet it has stagnated. This indicates that the extremely steep slope of the Dana Glacier, 30º, is prolonging movement.

Dana Glacier Ablation Study: 2021

Glaciers are sensitive indicators of the climate. When more snow accumulates than melts, the glacier can grow and will have a positive mass balance. On the other hand, when more snow melts than accumulates, the glacier shrinks (Hill, 2006). Sierra glaciers are now in a continuous state of shrinking. Currently, however, the cirques they occupy buffer this melting (Fountain, 2021). Avalanching can increase accumulation and offset, or lessen the effect of heavy melt. Cirques also provide shade which protects glaciers from solar radiation (Sharp, 1992). As the albedo of the glacier lowers, melt can be increased. Melt that exposes more bedrock, dirt, and rocks on the glacier surface will decrease albedo and increase melt (Sharp, 1992). Crevasse fields and ice falls, which increase surface roughness, can also cause increased melt (O'Neel, 2019). However the shady, sheltered environment of cirques can buffer many of these effects. Local topography can also help decrease ablation, the vertical melt of glacier ice. Features that can increase accumulation, high headwalls, and elevation or latitude are shown to diminish melt (Basagic, 2011). The Sierra glaciers that remain today all possess these features, and glaciers without these buffering effects have already melted away. The Dana Glacier has a particularly tall headwall.

I led a team to the Dana Glacier where we measured ablation through the placement and measurement of eight stakes over a five week period in the summer of 2021. Three poles were placed on July 11 using an ice auger. The precise amount of pole sticking above the ice surface and below the surface was recorded. The ice auger got stuck, so we returned a week later with replacement parts and placed and measured five more. A month after the initial placement we returned and re-measured the stakes. Results show large melt over the time period. The first week, when half the stakes were placed, shows dramatic melt as a heat wave was occurring at the time (Fig. 14).

	Ablation over 7/11/21 - 7/17/21			
Pole	Melt	days	Average daily melt at each pole	Average daily glacier melt (cm)
Green	56	6	9.33	8.78
Orange	53	6	8.83	
Gray	49	6	8.17	
Yellow	N/A	N/A	N/A	
Purple	N/A	N/A	N/A	
Blue	N/A	N/A	N/A	
Brown	N/A	N/A	N/A	
Pink	N/A	N/A	N/A	

	Ablation from 7/17/21 - 8/29/21			
Pole	Melt	Days	Average daily melt at each pole	Average daily glacier melt (cm)
Green	N/A	43		4.88
Orange	253	43	5.88	
Gray	196	43	4.56	
Yellow	186	43	4.33	
Purple	224	43	5.21	
Blue	193	43	4.49	
Brown	204	43	4.74	
Pink	213	43	4.95	

	Total Ablation from 7/11/21 - 8/29/21			
Pole	Melt	days	Average daily melt at each pole	Average daily glacier melt (cm)
Green	N/A	49	NA	4.92
Orange	306	49	6.24	
Gray	245	49	5.00	
Yellow	186	43	3.80	
Purple	224	43	5.21	
Blue	193	43	4.49	
Brown	204	43	4.74	
Pink	213	43	4.95	

Figure 14: results - note the increased melt in the first week of the heat wave.

The first week of measurements showed an average melt per day of 9 cm, while the average melt per day over the entire period was 5 cm. This shows that heightened melt rates correlated to the period of time when temperatures were the highest, indicating that glacier melt is responsive to air temperatures, making glaciers good indicators of the climate. With these measurements I was able to make predictions about the lifespan of the Dana Glacier. The average glacier ice melt season stretches approximately from early July to early October. Therefore we can estimate that total loss for the melt season at the Dana Glacier is approximately 4.5m. From my volume calculations made in 2020 we can estimate that the deepest part of the glacier is 31m thick. The glacier will not melt away linearly--as it gets smaller it will occupy increasingly shady areas being exposed to less solar radiation. This can also be slowed down or sped up by the size of the winter. However, in general I can project that in the next ten years most of the Dana Glacier will have melted away entirely.

The Dana Glacier has a taller-than-average headwall, so it gets significantly more shade than a glacier like Lyell which has a much smaller headwall. The Lyell headwall is 85 m tall compared to the 190m tall headwall at the Dana Glacier (Basagic, 2011). This has prolonged its life and will continue to shelter small scraps of the glacier for many years.

Dana Glacier Meltwater Contribution Study: 2018

Glaciers have a significant impact on riparian ecosystems down canyon. Meltwater from glaciers adds a small amount by volume to annual streamflow, but it is minimal in comparison to snowpack melt. However, the presence of glacial melt after the snowpack has melted away has a significant impact on riparian environments. Once all the snowpack has melted, glacial melt becomes a primary source of water for the riparian ecosystem (Fountain, 2021). This creates a buffering effect against warm and dry summers. While glaciers still remain at the heads of canyons, they can help offset the effects of a dry winter and hot summer. At high temperatures glacial melt will increase, offsetting the meltwater that was not gained over the winter (Fountain, 2017).

Glaciers can also delay peak runoff, as peak glacial melt season occurs after the snowpack has melted away (Fountain, 2017). Meltwater contributions from glaciers can also provide an indication of glacial health. Glaciers in equilibrium have a small impact on streamflow, while glaciers with a net mass loss contribute more meltwater to streams (Fountain, 2017). These impacts are not at their most extreme, considering the relatively small size of Sierra glaciers, yet they are big enough to have noticeable effects on the ecosystems around these glaciers.

In 2018, I evaluated the meltwater contributions of the Dana Glacier by comparing streamflow of Glacier Creek (directly downcanyon from the Dana Glacier) to streamflow in two other similar watersheds without glaciers at the head of the canyon. Streamflow was measured using the salt dilution method (Hudson, 2016).

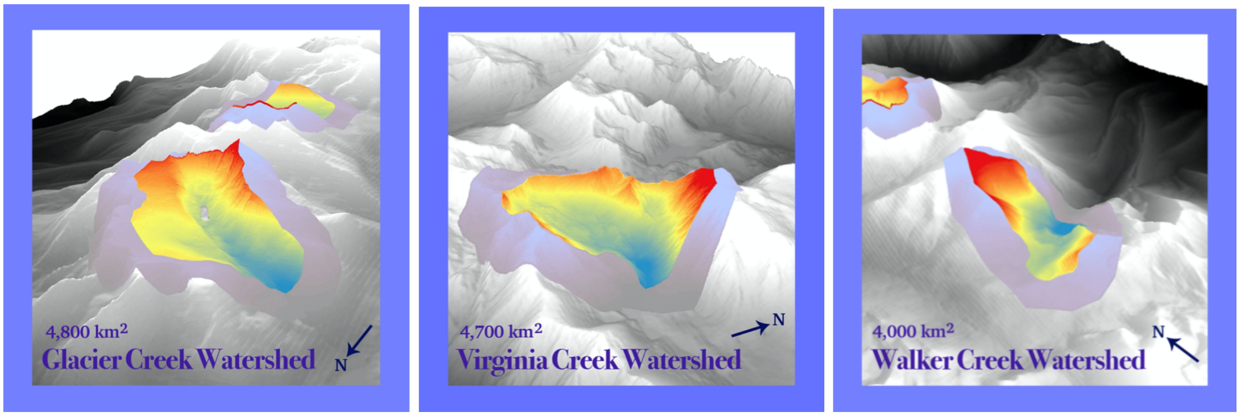


Figure 15: Watershed elevation and area profiles

Watershed	**Streamflow (m^3/s)**
Glacier Creek	0.07
Virginia Creek	0.02
Walker Creek	0.006

Figure 16: Streamflow

My results show that Dana Creek has a streamflow 10 times larger than streamflow in the Walker watershed and 4 times larger than the Virginia watershed. Measurements were taken in late fall 2018, after the snowpack had melted away. So, these measurements show that glacial melt has a significant impact on streamflow. Observations from the surrounding environments support this as well: Dana Creek has a rich riparian habitat, whereas the Walker and Virginia riparian habitats were much smaller and drier.

Virginia (left) and Walker (right) creeks - note drier conditions and little water in streams

Glacier creek - note large riparian habitat

Figure 17: Riparian habitats of 3 measured streams

Melt from the Dana Glacier is currently supporting a rich riparian habitat. But in the near future, the glacier will become so small that it will no longer contribute greatly to streamflow. This will have substantial negative impacts on the aquatic life and surrounding riparian habitat.

Conclusions

My research confirms that the Dana Glacier is still a glacier, as it possesses the defining characteristic of movement. It is a small, but measurable, amount of movement. This corresponds to the glacier's small total volume, $5.96 \times 10^5\ m^3$, and predicted average thickness of about 12 m. The Dana Glacier is melting quickly and is very susceptible to local temperature shifts; this has direct impacts on the stream and riparian habitat downcanyon. Glacial melt increases fall flow of Glacier Creek by about 4 to 10 times that of streamflow non-glaciated similarly sized watersheds.

The Dana Glacier has persisted this long because the cirque it occupies buffers the effects of the changing climate. Shrinkage continues to occur rapidly, but at a slower rate than it would were the glacier in a different location. While remnant pieces of the Dana Glacier that see little to no sun throughout the summer may last for many years, my projections predict that the great majority of the glacier will have almost entirely melted away in 10 years.

The Dana Glacier plays an important role in buffering the effects of dry summer conditions on riparian ecosystems. Melt from the Dana Glacier provides a consistent source of water throughout the summer and fall, causing Glacier Creek to flow even after the snowpack has melted. When this consistent water source ceases, the stream and surrounding riparian habitat will experience significant negative effects. Furthermore, my small town's tourist and recreation economy depends heavily on the environment created by several glacial streams in the Sierra. After these glaciers have melted away, my town will suffer greatly.

Glaciers are very sensitive indicators of climate change. The rapid melt and depletion of the Dana Glacier clearly illustrates the effect of warming temperatures in the Sierra. These changes directly indicate that climate change is already having major impacts on the Sierra that will only become more severe in the future.

References Cited

Avedievitch, N. and Stock, G., 2020, The retreat of Yosemite's Lyell and Maclure Glaciers: quantified using 3D surface fitting and historical photography: United States Geological Survey.

Basagic, Hassan. Personal zoom interview. 13 Oct. 2021.

Fountain, Andrew. Personal zoom interview. 7 Oct. 2021.

Basagic, H.J., and Fountain, A.G., 2011, Quantifying 20th century glacier change in the Sierra Nevada, California: Arctic, Antarctic, and Alpine Research, v. 43, no. 3, p. 317–330, doi: 10.1657/1938-4246-43.3.317.

Fountain, A.G., Glenn, B., and Basagic, H.J., 2017, The geography of glaciers and perennial snowfields in the American West: Arctic, Antarctic, and Alpine Research, v. 49, no. 3, p. 391–410, doi: 10.1657/aaar0017-003.

Glazner, A.F., and Stock, G.M., 2010, Geology underfoot in Yosemite National Park: Mountain Press, Missoula, Mont.

Guyton, B., 2001, Glaciers of california: Modern Glaciers, ice age glaciers, the origin of Yosemite Valley, and a glacier tour in the Sierra Nevada: University of California Press, Berkeley, CA.

Hill, M., 2006, Of Ice, *in* Geology of the Sierra Nevada, University of California Press, Berkeley, Calif.

Hudson, R., and Fraser, J., 2005, Introduction to Salt Dilution Gauging for Streamflow Measurement Part IV: The Mass Balance (or Dry Injection) Method: Streamline Watershed Management Bulletin, v. 9, no. 1.

McQuilkin, E., 2020, A Study of Glacial Movement Based on the Kuna and Dana Glaciers.

McQuilkin, E., 2019, Fall Flow: The Effect of Glacial Melt on Fall Flow.

National Park Service, 1933-1975, Report of Glacier Measurements (annual unpublished reports of glacier measurements, 1933-1975).

O'Neel, S., McNeil, C., Sass, L.C., Florentine, C., Baker, E.H., Peitzsch, E., McGrath, D., Fountain, A.G., and Fagre, D., 2019, Reanalysis of the US Geological Survey Benchmark Glaciers: Long-term insight into climate forcing of Glacier Mass Balance: Journal of Glaciology, v. 65, no. 253, p. 850–866, doi: 10.1017/jog.2019.66.

Phillips, F.M., Zreda, M.G., Benson, L.V., Plummer, M.A., Elmore, D., and Sharma, P., 1996, Chronology for fluctuations in late Pleistocene Sierra Nevada glaciers and Lakes: Science, v. 274, no. 5288, p. 749–751, doi: 10.1126/science.274.5288.749.

Raub, W., Brown, C.S., and Post, A., 2006, Inventory of glaciers in the Sierra Nevada, California: Open-File Report, doi: 10.3133/ofr20061239.

Sanders, J.W., Cuffey, K.M., MacGregor, K.R., Kavanaugh, J.L., and Dow, C.F., 2010, Dynamics of an alpine cirque glacier: American Journal of Science, v. 310, no. 8, p. 753–773, doi: 10.2475/08.2010.03.

Sharp, R.P., 1992, Living ice: Understanding glaciers and glaciation: Cambridge Univ. Pr., Cambridge.

Stock, Greg M., Robert Anderson, 2012, Yosemite's Melting Glaciers: Yosemite National Park. https://files.cfc.umt.edu/cesu/NPS/CU/2009/09_11Anderson_YOSE_glaciers_fnl%20rpt.pdf.

Stock, Greg. Personal communication. 2020-2021.