Streams, Springs, and Volcanic Lakes for Volcano Monitoring

Chapter F of
Recommended Capabilities and Instrumentation for Volcano Monitoring in the United States

Scientific Investigations Report 2024–5062

U.S. Department of the Interior
U.S. Geological Survey

Cover. U.S. Geological Survey hydrologist recording data at an unnamed warm spring on the north flank of Mount St. Helens, Washington, where in-situ measurements of conductivity, temperature, and depth were obtained at hourly frequency from 2009 to 2017. Photograph by K. Spicer, U.S. Geological Survey, September 22, 2016. Background image shows a typical view of the 2008–2018 lava lake in the Overlook crater within Halemaʻumaʻu, Kīlauea. Photograph taken from a helicopter by Tim Orr, U.S. Geological Survey, on August 16, 2013.

Streams, Springs, and Volcanic Lakes for Volcano Monitoring

By Steven E. Ingebritsen and Shaul Hurwitz

Chapter F of

Recommended Capabilities and Instrumentation for Volcano Monitoring in the United States

Edited by Ashton F. Flinders, Jacob B. Lowenstern, Michelle L. Coombs, and Michael P. Poland

Scientific Investigations Report 2024–5062

U.S. Department of the Interior
U.S. Geological Survey

U.S. Geological Survey, Reston, Virginia: 2024

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov.

Suggested citation:
Ingebritsen, S.E., and Hurwitz, S., 2024, Streams, springs, and volcanic lakes for volcano monitoring, chap. F *of* Flinders, A.F., Lowenstern, J.B., Coombs, M.L., and Poland, M.P., eds., Recommended capabilities and instrumentation for volcano monitoring in the United States: U.S. Geological Survey Scientific Investigations Report 2024–5062–F, 9 p., https://doi.org/10.3133/sir20245062f.

ISSN 2328-031X (print)
ISSN 2328-0328 (online)

Contents

Figures

Abbreviations

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CTD	conductivity, temperature, and depth
HD-YLAKE	Hydrothermal Dynamics of Yellowstone Lake
NWIS	National Water Information System
ROV	remotely operated vehicle
RV	research vessel
UAS	unoccupied aircraft system
USGS	U.S. Geological Survey

Chapter F

Streams, Springs, and Volcanic Lakes for Volcano Monitoring

By Steven E. Ingebritsen and Shaul Hurwitz

Introduction

Volcanic unrest can trigger appreciable change to surface waters such as streams, springs, and volcanic lakes. Magma degassing produces gases and soluble salts that are absorbed into groundwater that feeds streams and lakes. As magma ascends, the amount of heat and degassing will increase, and so will any related geochemical and thermal signal. Subsurface magma movement can cause pressurization that alters hydrostatic head and may induce groundwater discharge. Fluid-pressure changes have been linked to distal volcano-tectonic earthquakes (White and McCausland, 2016; Coulon and others, 2017) and phreatic eruptions (for example, Yamaoka and others, 2016). Clearly, changes in groundwater and surface waters are both indicators of unrest and clues to how and where magma is rising toward the surface. Where possible, it is prudent to incorporate real-time hydrologic data into multiparameter monitoring of restless volcanoes. Hydrologic dynamics can also be tracked by changes in groundwater levels that are commonly measured in shallow boreholes (see chapter K, this volume, on boreholes; Hurwitz and Lowenstern, 2024).

Although inferred to be common, relatively few volcano-hydrology anomalies are well documented, and many are essentially anecdotal (Newhall and others, 2001), reflecting the fact that high-resolution time series remain rare. Extreme examples include the 2008 eruption of Nevado del Huila, Colombia, where relatively minor phreatomagmatic eruptions were accompanied by expulsion of as much as 300 million cubic meters of groundwater from fissures high on the volcano (Worni and others, 2011), generating large lahars. Substantial decreases in flow rate from springs about 8 kilometers from the summit of Mayon Volcano, Philippines, have been noted before most eruptions in the 20th century (Newhall and others, 2001). Stream monitoring at Redoubt Volcano in 2009 allowed Werner and others (2012) to recognize that groundwater was unable to absorb (or scrub) the high flux of volcanic gas and that a high CO_2/SO_2 precursor signal had been evident for 5 months prior to the eruption. A key to better interpreting hydrologic anomalies—or even identifying them—is therefore obtaining adequate baseline data.

Most hydrologic monitoring at U.S. volcanoes has been accomplished by intermittent sampling surveys with annual or less frequent sampling (for example, https://hotspringchem.wr.usgs.gov/index.php). More frequent sampling, however, generally is needed to establish reliable baselines. A recent hydrologic and hydrothermal monitoring experiment at 25 sites and 10 of the 12 level 4 (very high threat) volcanoes in the U.S. portion of the Cascade Range demonstrated that there is sufficient temporal variability in hydrothermal fluxes, even during quiescent periods, that one-time measurements will commonly have limited interpretive value (Crankshaw and others, 2018). Thus, surveys are best augmented with data from streamgages (for example, Evans and others, 2004; Bergfeld and others, 2008). Streamflow (water discharge) data allow measured temperature and specific conductance to be converted to heat and solute mass fluxes, which could be insightful parameters for detecting anomalous activity (McCleskey and others, 2012). At the Yellowstone Caldera, long-term monitoring of river solutes has allowed calculation of the chloride flux, a proxy for heat discharge (Hurwitz and others, 2007; McCleskey and others, 2016) from the subsurface magma. This is readily accomplished because data from streamgages are continuously recorded and archived by the U.S. Geological Survey (USGS) National Water Information System (NWIS) (USGS, 2024).

Similar studies on stratovolcanoes or shield volcanoes would be scientifically useful, and yet are logistically challenging, requiring streamgages on numerous radial drainages complemented by either frequent manual sampling or numerous deployments of equipment to measure water temperature and specific conductance as a proxy for water chemistry. Another challenge is that some volcanic areas, especially shield volcanoes, are characterized by near-surface porous rocks and soils, such that surface streams are rare and replaced by distant, dilute large-volume springs with only a trace of any original volcanically sourced water (Manga, 2001; Hurwitz and others, 2021).

Volcanic lakes are worthy of special attention for monitoring efforts, as their temperature and composition can provide evidence of increased flux of volatile-rich fluids from below. Quantifying changes in volatile and heat release from magma can be simpler in lakes than for volcanoes with radial drainages and no major lakes. Moreover, volcanic lakes pose a range of hazards themselves, including phreatomagmatic eruptions, debris flows, flank collapse, tsunamis, and toxic gas release (Mastin and Witter, 2000; Delmelle and others, 2015; Manville, 2015; Rouwet and others, 2015)—hazards that have historically been responsible for substantial loss of life at many volcanoes worldwide (Manville, 2015). Catastrophic CO_2 release at Lake Nyos, Cameroon, in 1986 suffocated about 1,750 people and about 3,500 livestock and was probably triggered by a large landslide into the gas-saturated lake (Kling and others, 1987; Evans and others, 1993). Gas-charged springs in Soda Bay within Clear Lake (California) have caused almost a dozen deaths to bathers in the past hundred years (ABC News, 2000). A 2005 example of lake overturn and abundant gas release was documented at Mount Chiginagak in Alaska (Schaefer and others, 2008) but did not result in any human casualties. Although thermally stratified lakes, which promote trapping of exsolved magmatic gas, tend to develop in tropical regions, the phenomenon can also arise where salinity creates meromixis (a condition in which a lake does not mix completely), as occurs in Mono Lake, California (Jellison and Melack, 1993; Jellison and others, 1998).

If magma erupts or flows into a lake, the interaction between hot magma and cold water can be explosive (Mastin and others, 2004; Zimanowski and others, 2015) and substantially expand the area affected by the eruption. Another hazard is the breaching of crater rims by landslides triggered by volcanic and (or) seismic activity. Under some circumstances, substantial volumes of water can be displaced, leading to large floods and lahars. Late Holocene lake flooding from Aniakchak Crater in the Alaska Peninsula (Waythomas, 2022) and from Paulina Lake in Newberry Crater, Oregon (Chitwood and Jensen, 2000), caused by the failure of outlet sills, testify to the substantial hazards at lake-filled calderas.

Several volcanic systems in the United States host lakes known to receive heat and gas from underlying magma. These lakes vary widely in area, depth, and chemical composition. Lakes are present at level 4 volcanoes, including Crater Lake and Newberry Volcano in Oregon; Yellowstone Caldera in Wyoming; Long Valley Caldera, Clear Lake volcanic field, Medicine Lake, and Salton Buttes in California; and Aniakchak Crater, Mount Katmai, Fisher Caldera, Mount Okmok, and Kaguyak Crater, among others, in Alaska. A water lake was present in Halemaʻumaʻu, the crater of Kīlauea, Hawaiʻi (fig. F1), from October 2019 to December 2020. Level 3 volcanoes with lakes include Mono Lake volcanic field (Calif.), Mount Bachelor (Ore.), Ukinrek Maars and Mount Chiginagak (Alaska), and Soda Lake (Nevada). In addition, there are lakes at many levels 1 and 2 volcanoes. In the United States, there are no strongly acidic lakes that receive abundant input of magmatic gas, such as those found at Mount Ruapehu (New Zealand), Ijen and Kelud (Indonesia), and Poás (Costa Rica). Nevertheless, many contain fluids that provide clues to magmatic processes below.

Since publication of a previous report on recommended instrumentation for volcano monitoring (Moran and others, 2008), continuous hydrologic monitoring has become increasingly feasible. However, changes in water pressure, temperature, and chemistry remain, in general, poorly studied phenomena at volcanoes (Sparks, 2003; National Academies of Sciences, Engineering, and Medicine, 2017). Recent efforts by the USGS have included the temporary study of Cascade Range volcanoes, which included frequent (15 minute to hourly) temporal sampling of temperature, depth, and conductivity (Crankshaw and others, 2018; Ingebritsen and Evans, 2019). At Yellowstone Caldera, many streamgages have now added thermistors and specific conductance sensors, allowing estimation of time-dependent chloride flux as a proxy for variations in subsurface heat flux (McCleskey and others, 2012, 2016). Efforts to better understand lakes have also accelerated, with bathymetric mapping and sampling carried out at several locations in the United States. Especially thorough work was done at Yellowstone Lake thanks to the Hydrothermal Dynamics of Yellowstone Lake (HD-YLAKE, https://hdylake.org) project, funded primarily by the National Science Foundation. In addition to geophysical surveys and recovery of cores and other samples, HD-YLAKE investigations included remotely operated vehicle (ROV) investigations of hydrothermal vents on the lake floor (fig. F2). Data collected by the ROV provided a better understanding of the thermal and chemical influx from lake-bottom hydrothermal systems (Sohn and others, 2017).

Figure F1. Photograph showing U.S. Geological Survey Hawaiian Volcano Observatory geologist measuring lake-surface temperatures using a thermal camera at Kīlauea’s short-lived crater lake. Flat areas of lava flow surfaces beyond and above the lake are former sections of the crater floor of Halemaʻumaʻu that subsided hundreds of meters during the 2018 caldera collapse. Yellow areas are regions of substantial sulfur precipitation. Photograph by K. Mulliken, U.S. Geological Survey, December 18, 2019.

Figure F2. Photograph showing scientists aboard research vessel (RV) *Annie II* monitoring control room video of the remotely operated vehicle (ROV) *Yogi* being deployed in Yellowstone Lake, Wyoming, August 2017. The ROV made heat-flow measurements at a thermal field on the lake floor as part of the multiyear Hydrothermal Dynamics of Yellowstone Lake (HD-YLAKE) project (Sohn and others, 2017). Photograph by S. Hurwitz, U.S. Geological Survey.

In this chapter, we focus on detecting changes in the chemistry, temperature, discharge, or water levels of streams, springs, and lakes that can be caused by seismicity, volumetric strains, or increases in gas flux associated with ascending magma. There is unavoidable overlap with other chapters of this report. Samples of water and gas can also be obtained in boreholes (chapter K, this volume; Hurwitz and Lowenstern, 2024), both shallow and deep. Gas monitoring (chapter E, this volume; Lewicki and others, 2024) relies in part on samples from springs and wells, particularly where measurable gas plumes are absent. Water acts as a trigger and lubricant for landslides and sediment-rich floods, and so hydrology has obvious relevance for lahar monitoring, as discussed in chapter H (this volume; Thelen and others, 2024). Shared situational awareness among scientists engaged in geophysical, gas, and hydrologic monitoring will improve overall understanding of the volcanic hazard.

Instrumentation Relevant to Streams, Springs, and Lakes

Most continuous, long-term hydrologic monitoring to date has emphasized a subset of relatively easy-to-measure parameters, namely water level, temperature, and electrical conductivity. Commercial off-the-shelf instrumentation now includes devices that can measure conductivity, temperature, and depth (that is, CTD) within a stream, lake, or well. They typically contain a memory cache that can store several years of data collected at hourly intervals (or less time for more frequent sampling), and data can be retrieved in the field without removing the sensor itself. When needed, these data can be telemetered in real time. Site conditions on volcanoes commonly pose severe challenges for continuous sensors, including high-temperature and corrosive waters and energetic and (or) sediment-laden streams. However, sensor technology and reliability continue to improve.

Water flow rates are measured through streamgaging techniques where the rate of water flow is measured at a standard depth above the streambed and combined with a survey of the stream's cross-sectional area. By performing similar measurements at different flow rates (usually at different times of the year), a rating curve can be developed to allow measurements of a stream's stage to be correlated with water discharge. A typical USGS NWIS installation at a streamgage measures flow rate but can also include sensors for air and water temperature, precipitation, and specific conductance (electrical conductivity). These parameters can be converted to heat or mass flux as well as ionic species of interest (McCleskey and others, 2012). Ion-specific probe technology continues to evolve, and it may soon be possible to directly sense and quantify concentrations of species of interest, such as dissolved inorganic carbon, chloride, sulfate, boron, arsenic, and mercury.

Another useful instrument for background or long-term studies is an autosampler that pumps water into a series of sample containers at a set interval (hourly, daily, weekly, and so on) for later manual retrieval and laboratory analysis of a time series (Ono and others, 2020). This automation greatly enhances the efficiency of baseline investigations to understand the dynamics of hydrothermal discharge that may be characterized by diurnal, seasonal, or climatic variations.

Recommended Capabilities

Detect Changes in Chemistry, Temperature, Discharge, or Water Levels of Streams and Springs

During unrest, information on hydrologic changes represents a key part of multiparameter monitoring. Such data can reveal important subsurface changes to the magmatic system, with relevance to eruption forecasts. Ideally, hydrologic data will be automatically collected and delivered to the observatory along with geophysical data. However, only rarely is this currently the case. Hydrologic monitoring, like gas monitoring, generally requires more human involvement than geophysical monitoring; only limited information can be obtained from unattended instrumentation. Safety factors can complicate rapid response during unrest, limiting where samples can be obtained and new instrumentation installed. Another persistent challenge is latency with respect to laboratory-based geochemical measurement of key constituents, such as isotope ratios.

To optimize sampling, and placement of appropriate instrumentation during unrest, it is important to develop an understanding of baseline hydrothermal activity in the volcanic system. This requires a consistent program of water sampling for chemical analysis and extended deployments of samplers. The relation between geochemical and thermal anomalies in water and volcanic unrest may be difficult to assess without volcano-specific conceptual models and sufficient baseline data. Moreover, water sampling during unrest episodes at Mammoth Mountain, Calif. (Evans and others, 2002); Three Sisters, Ore. (Evans and others, 2004); and Mount St. Helens, Wash. (Bergfeld and others, 2008), has shown that not all springs and streams on a volcano will respond to unrest. This makes it difficult to determine in advance the optimal placement of monitoring sites.

Long (multiyear) and high-resolution (hourly or better) hydrologic time series are ideal for determining whether hydrologic anomalies are related to volcanic unrest, including residual effects of previous intrusions or eruptions, or to nonvolcanic phenomena such as changes in meteoric-water flux, tectonic earthquakes, and anthropogenic influences. Yet sampling logistics are highly variable. Although some sampling sites are within reach of roads (some locations at Yellowstone National Park and Clear Lake volcanic field), others are high on the slopes of remote volcanoes like Glacier Peak, Wash. Although sensor technology is fast evolving, there are still few commercial off-the-shelf instruments that can measure relevant parameters and sustain multiyear deployment in sometimes hot, chemically aggressive waters. For these and other reasons, hydrologic monitoring strategies are still evolving, and a generic standard has yet to be defined and agreed upon.

Recommendations

At levels 1 and 2 volcanoes, we recommend an inventory of spring, stream, and well sites to identify those with indications of ongoing magmatic influence such as elevated $^3He/^4He$ ratios, large fluxes of magmatic CO_2, or anomalous heat fluxes. This would require a field visit, sampling, basic measurements (temperature, pH, and specific conductance), and subsequent laboratory analysis for major element chemistry and isotope ratios, potentially including those of carbon, oxygen, hydrogen, and helium. Level 3 volcanoes would ideally have similar background studies, combined with resampling every 5 to 10 years to gradually define baseline conditions and develop rating curves. Those springs and streams with clear magmatic signals and accessible sites may be targeted for longer term studies with deployed commercial off-the-shelf CTD sensors and autosamplers. At level 4 volcanoes, appropriate sites would ideally be characterized such that baseline parameters allow quantitative assessment of variability caused by factors such as tectonic earthquakes and semidiurnal and seasonal (for example, barometric and tidal) influences. Regular sampling surveys along all major drainages will better define baseline characteristics and behavior. We recommend installation of instrumentation for multiyear (3–5 year) periods to collect hourly (or better) information on heat flux and magmatically derived solutes. Sampling surveys should include water chemistry and temperature. Combined with measurements of spring- and streamflow, these surveys would permit calculation of the mass flow rate of magma-derived constituents. Moreover, at selected level 4 volcanoes, we encourage continuous real-time monitoring of hydrologic parameters, targeting springs, and (or) streams that are known or likely to be influenced by magmatic processes. The number and type of instruments would be tailored to site-specific considerations and reflect evolving technology. Periodic sampling and streamgaging would ideally be performed to calibrate sensors and establish rating curves for dissolved species of interest and streamflow, allowing mass flowrates of magma-derived constituents to be calculated continuously. Because many level 4 volcanoes are remote, observatories would need to prioritize work based on relative threat level, exposed population, logistical complexity, cost, and other factors.

Monitor and Characterize Geochemical and Geophysical Changes in Volcanic Lakes

Changes in volcanic lakes, for example deformation on the lake floor, are by nature less accessible than changes in springs and streams. The three-dimensional nature of volcanic lakes similarly requires different approaches, including geophysical techniques, to monitor and characterize changes. Baseline data would help guide future monitoring and hazard assessment. These include bathymetric and heat-flow mapping, characterization of hydrothermal vents and the three-dimensional distribution of temperature, salinity, and dissolved species of magmatic origin in lake waters. These measurements will enable quantification of heat and gas into, and out of, the lake—information that is required to assess the potential for lake overturns and release of toxic gases into the atmosphere.

Many of these basic studies and follow-up monitoring operations would build upon developments in oceanic research, including advances in seafloor geodesy (Bürgmann and Chadwell, 2014) and the establishment of a cabled observatory at Axial Seamount off the Pacific Northwest coast (Kelley and others, 2014). Lessons can also be learned from the 1-year deployment of lake-bottom seismometers in Yellowstone Lake (for example, Smalls and others, 2019) and from echo-sounder deployments at Kelud, Indonesia, which tracked changes in gas discharge into the crater lake several months before volcanic eruptions (Vandemeulebrouck and others, 2000; Caudron and others, 2012). Echo sounding takes advantage of the large acoustic impedance contrast between water and gas bubbles. All these technological developments should help to establish monitoring systems unique to volcanic lakes and will likely be best accomplished with collaborators from the ocean-sciences community.

Volcanic and (or) magmatic heat and gas inputs into active volcanic lakes are either focused through hydrothermal vents or are more diffuse throughout most of the lakebed (for example, Pasternack and Varekamp, 1997; Varekamp, 2015). Lakes that are hydrothermally active and deemed to pose a threat to communities and infrastructure should be monitored by continuous instruments. Fundamental data needed to monitor volcanic lakes include temperature, water level, water depth, and visual observations of color and physical state. The temperatures of volcanic lakes are determined primarily by the magnitude of the volcanic heat influx relative to the surface area of the lake; other factors include the temperature and influx rate of groundwater or surface water. Smaller lakes exhibit rapid temperature increases with only small heat inputs, whereas large lakes are buffered against variations in heat input (Pasternack and Varekamp, 1997). Changes in heat and gas discharge into lakes can be early indicators of ascending magma. Total emission rates can be substantially underestimated, and the chemical and isotopic composition of the gas altered, when gases exsolved from magma are dissolved into lake water instead of escaping directly into the atmosphere (for example, Varekamp, 2015). Lake-floor deformation stations and chemical sensors that can track changes in the composition of thermal water flowing into lakes would also provide valuable information.

Because lake levels are influenced by climate and weather, meteorological stations are also needed near monitored lakes. Geophysical surveys (primarily seismic reflection and magnetics) can provide additional information on the location of hydrothermal vents and deposits (for example, Johnson and others, 2003; Brothers and others, 2009).

Instrumentation

Cameras are essential for real-time visual monitoring of changes in volcanic lakes; they provide valuable context for evaluating changes in other monitoring data (see chapter G, this volume, on tracking surface changes; Orr and others, 2024). Image acquisition rates must be tailored to the possible timescales of activity. Quiescent baseline activity could be tracked with low image rates (images every few minutes to tens of minutes), but more dynamic activity, such as lake agitation or small explosions, requires higher rates (one or more images every second) and higher resolution. A hybrid approach in bandwidth-limited scenarios involves low image rates transmitted over a network coupled with high image rates stored locally at the camera site and collected manually for later analysis.

Quantitatively tracking lake color can be accomplished with a handheld colorimeter. Objective measurements of color may presage future hazards, as lake color can reflect water chemistry (Ohsawa and others, 2010). The USGS Hawaiian Volcano Observatory used a Konica-Minolta CS-160 colorimeter to measure color at Kīlauea's short-lived summit lake during field campaigns in 2019. Such colorimeters might be modified to operate in a continuous mode with data transmitted to the observatory.

Thermal cameras offer a tool for remote temperature monitoring if the lake is not approachable. Thermal cameras transmitting images in real time to the observatory provide continuous monitoring (Patrick and others, 2014). One benefit of thermal imaging is that the data can be collected at night. Thermal data can also be obtained via satellite; for example, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data were used to reconstruct temperatures at Copahue crater lake (on the border of Argentina and Chile) during a quiescent period between eruptions in 2000 and 2012 (Candela-Becerra and others, 2020). The analysis revealed surface temperature variations of as high as 15 degrees Celsius in two different periods and a substantial temperature decrease prior to the December 2012 eruption.

Gas flux from lakes can be monitored by techniques outlined in chapter E on gas monitoring (this volume; Lewicki and others, 2024), including multicomponent gas analyzer systems, accumulation chambers (fig. F3), and eddy covariance. Gas flow near vents could also be monitored by hydroacoustic and echo-sounding methods (for example, Rouwet and others, 2014, and references therein).

Figure F3. Photograph showing U.S. Geological Survey California Volcano Observatory geologist measuring CO_2 flux on the surface of East Lake, Newberry Crater, Oregon. Photograph by L. Clor, U.S. Geological Survey, July 29, 2020.

Unoccupied aircraft systems (UAS) (discussed in chapter L, this volume; Diefenbach, 2024) offer a new means of monitoring hydrologic activity at volcanic lakes through direct water sampling. Thermal cameras onboard UAS can provide near-field remote measurements of water temperature, and repeat surveys can be flown for temperature-change detection. UAS also facilitate direct sampling to support geochemical monitoring of volcanic lakes (for example, Terada and others, 2018; Nadeau and others, 2020).

Recommendations

Lake monitoring is not required at every volcano; relatively few volcanoes have lakes, and some of those are in remote areas and pose little risk. There are, however, some volcanic lakes where the hazards could affect society. Monitoring of those lakes would ideally be done at a level commensurate with the associated risk.

No continuous monitoring is recommended for lakes on levels 1 and 2 volcanoes, but background data would ideally be collected consistent with the goals for detecting changes in streams and springs. At lakes on level 3 volcanoes, we recommend characterizing baseline geochemical and geophysical properties to guide future monitoring. Baseline surveys would ideally include bathymetric and heat-flow mapping, identification of hydrothermal vents, and, in some cases, mapping the three-dimensional distribution of temperature, salinity, and dissolved gas. For lakes at level 4 volcanoes, we recommend the same background surveys as for lakes on level 3 volcanoes but increasing the degree to which continuous real-time data are collected. The number and type of instruments should be tailored to site-specific considerations and reflect evolving technology, but would ideally include temperature, surface activity, gas emissions, and chemistry, supplemented by regular surveys and sampling as appropriate. At lakes with active hydrothermal vents, campaign and (or) real-time measurements of vent temperature, discharge, and chemistry would be made to quantitatively assess variability caused by factors such as magmatic activity, tectonic earthquakes, and semidiurnal and seasonal (for example, barometric pressure and tidal) influences.

General Recommendations and Considerations

In this chapter, we make suggestions for background studies, temporary deployments, and potential real-time data from hydrologic features to inform volcano monitoring. There will be inevitable overlap with the strategies and goals outlined in chapter E of this volume on monitoring gas (Lewicki and others, 2024), as water and gases can reflect geothermal and magma-sourced components. Moreover, hydrologic monitoring might include looking at dissolved gases, and gas monitoring would need to consider the effects of gas-water-rock interaction, thus requiring careful coordination for acquisition of the optimal parameters. One difference between monitoring gases and water is that the latter may require a more regional approach, recognizing that water and springs may discharge miles away from volcanic centers, whereas gas flow is generally more vertically directed in the crust and studies would be focused higher on the volcanic edifice.

References Cited

ABC News, 2000, Hot spring may have claimed another victim: ABC News, September 25, 2000, accessed April 15, 2024, at https://abcnews.go.com/Technology/story?id=119923&page=1.

Bergfeld, D., Evans, W.C., McGee, K.A., and Spicer, K.R., 2008, Pre- and post-eruptive investigations of gas and water samples from Mount St. Helens, Washington, 2002 to 2005, *in* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled—The renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750, p. 523–542, https://doi.org/10.3133/pp175025.

Brothers, D.S., Driscoll, N.W., Kent, G.M., Harding, A.J., Babcock, J.M., and Baskin, R.L., 2009, Tectonic evolution of the Salton Sea inferred from seismic reflection data: Nature Geoscience, v. 2, p. 581–584, https://doi.org/10.1038/ngeo590.

Bürgmann, R., and Chadwell, D., 2014, Seafloor geodesy: Annual Review of Earth and Planetary Sciences, v. 42, p. 509–534, https://doi.org/10.1146/annurev-earth-060313-054953.

Candela-Becerra, L.J., Toyos, G., Suárez-Herrera, C.A., Castro-Godoy, S., and Agusto, M., 2020, Thermal evolution of the Crater Lake of Copahue Volcano with ASTER during the last quiescence period between 2000 and 2012 eruptions: Journal of Volcanology and Geothermal Research, v. 392, article no. 106752, https://doi.org/10.1016/j.jvolgeores.2019.106752.

Caudron, C., Mazot, A., and Bernard, A., 2012, Carbon dioxide dynamics in Kelud volcanic lake: Journal of Geophysical Research, Solid Earth, v. 117, no. B5, https://doi.org/10.1029/2011JB008806.

Chitwood, L.A., and Jensen, R.A., 2000, Large prehistoric flood along Paulina Creek, Newberry Volcano, Oregon—What's New at Newberry Volcano, Oregon: Guidebook for the Friends of the Pleistocene Eighth Annual Pacific Northwest Cell Field Trip, p. 31–40.

Coulon, C.A., Hsieh, P.A., White, R., Lowenstern, J.B., and Ingebritsen, S.E., 2017, Causes of distal volcano-tectonic seismicity inferred from hydrothermal modeling: Journal of Volcanology and Geothermal Research, v. 345, p. 98–108, https://doi.org/10.1016/j.jvolgeores.2017.07.011.

Crankshaw, I.M., Archfield, S.A., Newman, A.C., Bergfeld, D., Clor, L.E., Spicer, K.R., Kelly, P.J., Evans, W.C., and Ingebritsen, S.E., 2018, Multi-year high-frequency hydrothermal monitoring of selected high-threat Cascade Range volcanoes: Journal of Volcanology and Geothermal Research, v. 356, p. 24–35, https://doi.org/10.1016/j.jvolgeores.2018.02.014.

Diefenbach, A.K., 2024, Special topic—Unoccupied aircraft systems, chap. L *of* Flinders, A.F., Lowenstern, J.B., Coombs, M.L., and Poland, M.P., eds., Recommended capabilities and instrumentation for volcano monitoring in the United States: U.S. Geological Survey Scientific Investigations Report 2024–5062–L, 5 p., https://doi.org/10.3133/sir20245062l.

Delmelle, P., Henley, R.W., and Bernard, A., 2015, Volcano-related lakes, chap. 48 *of* Sigurdsson, H., Houghton, B.F., McNutt, S.R., Rymer, H., and Stix, J., The Encyclopedia of Volcanoes (2d ed.): San Diego, Academic Press, p. 851–864, https://doi.org/10.1016/B978-0-12-385938-9.00048-1.

Evans, W.C., Kling, G.W., Tuttle, M.L., Tanyileke, G., and White, L.D., 1993, Gas buildup in Lake Nyos, Cameroon—The recharge process and its consequences: Applied Geochemistry, v. 8, no. 3, p. 207–221, https://doi.org/10.1016/0883-2927(93)90036-G.

Evans, W.C., Sorey, M.L., Cook, A.C., Kennedy, B.M., Shuster, D.L., Colvard, E.M., White, L.D., and Huebner, M.A., 2002, Tracing and quantifying magmatic carbon discharge in cold groundwaters—Lessons learned from Mammoth Mountain, USA: Journal of Volcanology and Geothermal Research, v. 114, nos. 3–4, p. 291–312, https://doi.org/10.1016/S0377-0273(01)00268-2.

Evans, W.C., van Soest, M.C., Mariner, R.H., Hurwitz, S., Ingebritsen, S.E., Wicks, C.W., Jr., and Schmidt, M.E., 2004, Magmatic intrusion west of Three Sisters, central Oregon, USA—The perspective from spring geochemistry: Geology, v. 32, p. 69–72, https://doi.org/10.1130/G19974.1.

Hurwitz, S., and Lowenstern, J.B., 2024, Special topic—Boreholes, chap. K *of* Flinders, A.F., Lowenstern, J.B., Coombs, M.L., and Poland, M.P., eds., Recommended capabilities and instrumentation for volcano monitoring in the United States: U.S. Geological Survey Scientific Investigations Report 2024–5062–K, 5 p., https://doi.org/10.3133/sir20245062k.

Hurwitz, S., Lowenstern, J.B., and Heasler, H., 2007, Spatial and temporal geochemical trends in the hydrothermal system of Yellowstone National Park—Inferences from river solute fluxes: Journal of Volcanology and Geothermal Research, v. 162, nos. 3–4, p. 149–171, https://doi.org/10.1016/j.jvolgeores.2007.01.003.

Hurwitz, S., Peek, S.E., Scholl, M.A., Bergfeld, D., Evans, W.C., Kauahikaua, J.P., Gingerich, S.B., Hsieh, P.A., Lee, R.L., Younger, E.F., and Ingebritsen, S.E., 2021, Groundwater dynamics at Kīlauea Volcano and vicinity, Hawai‘i, chap. F *of* Patrick, M., Orr, T., Swanson, D., and Houghton, B., eds., The 2008–2018 summit lava lake at Kīlauea Volcano, Hawai‘i: U.S. Geological Survey Professional Paper 1867, 28 p., https://doi.org/10.3133/pp1867F.

Ingebritsen, S.E., and Evans, W.C., 2019, Potential for increased hydrothermal arsenic flux during volcanic unrest—Implications for California water supply: Applied Geochemistry, v. 108, article no. 104384, https://doi.org/10.1016/j.apgeochem.2019.104384.

Jellison, R., and Melack, J.M., 1993, Meromixis in hypersaline Mono Lake, California. 1. Stratification and vertical mixing during the onset, persistence, and breakdown of meromixis: Limnology and Oceanography, v. 38, p. 1008–1019, https://doi.org/10.4319/lo.1993.38.5.1008.

Jellison, R., Romero, J., and Melack, J.M., 1998, The onset of meromixis during restoration of Mono Lake, California—Unintended consequences of reducing water diversions: Limnology and Oceanography, v. 43, p. 706–711, https://doi.org/10.4319/lo.1998.43.4.0706.

Johnson, S.Y., Stephenson, W.J., Morgan, L.A., Shanks, W.C., III, and Pierce, K.L., 2003, Hydrothermal and tectonic activity in northern Yellowstone Lake, Wyoming: Geological Society of America Bulletin, v. 115, p. 954–971, https://doi.org/10.1130/B25111.1.

Kelley, D.S., Delaney, J.R. and Juniper, S.K., 2014, Establishing a new era of submarine volcanic observatories—Cabling Axial Seamount and the Endeavour Segment of the Juan de Fuca Ridge: Marine Geology, v. 352, p. 426–450, https://doi.org/10.1016/j.margeo.2014.03.010.

Kling, G.W., Clark, M.A., Wagner, G.N., Compton, H.R., Humphrey, A.M., Devine, J.D., Evans, W.C., Lockwood, J.P., Tuttle, M.L., and Koenigsberg, E.J., 1987, The 1986 Lake Nyos gas disaster in Cameroon, West Africa: Science, v. 236, no. 4798, https://doi.org/10.1126/science.236.4798.169.

Lewicki, J.L., Kern, C., Kelly, P.J., Nadeau, P.A., Elias, T., and Clor, L.E., 2024, Volcanic gas monitoring, chap. E *of* Flinders, A.F., Lowenstern, J.B., Coombs, M.L., and Poland, M.P., eds., Recommended capabilities and instrumentation for volcano monitoring in the United States: U.S. Geological Survey Scientific Investigations Report 2024–5062–E, 11 p., https://doi.org/10.3133/sir20245062e.

Manga, M., 2001, Using springs to study groundwater flow and active geologic processes: Annual Review of Earth and Planetary Sciences, v. 29, p. 201–228, https://doi.org/10.1146/annurev.earth.29.1.201.

Manville, V., 2015, Volcano-hydrologic hazards from volcanic lakes, *in* Volcanic Lakes: Springer, Berlin, Heidelberg, p. 21–71, https://doi.org/10.1007/978-3-642-36833-2_2.

Mastin, L.G., Christiansen, R.L., Thornber, C., Lowenstern, J., and Beeson, M., 2004, What makes hydromagmatic eruptions violent? Some insights from the Keanakāko‘i Ash, Kīlauea Volcano, Hawai‘i: Journal of Volcanology and Geothermal Research, v. 137, p. 15–31.

Mastin, L.G., and Witter, J.B., 2000, The hazards of eruptions through lakes and seawater: Journal of Volcanology and Geothermal Research, v. 97, p. 195–214, https://doi.org/10.1016/S0377-0273(99)00174-2.

McCleskey, R.B., Clor, L.E., Lowenstern, J.B., Evans, W.C., Nordstrom, D.K., Heasler, H., and Huebner, M.A., 2012, Solute and geothermal flux monitoring using electrical conductivity in the Madison, Firehole, and Gibbon Rivers, Yellowstone National Park: Applied Geochemistry, v. 27, no. 12, p. 2370–2381, https://doi.org/10.1016/j.apgeochem.2012.07.019.

McCleskey, R.B., Lowenstern, J.B., Schaper, J., Nordstrom, D.K., Heasler, H.P., and Mahony, D., 2016, Geothermal solute flux monitoring and the source and fate of solutes in the Snake River, Yellowstone National Park, WY: Applied Geochemistry, v. 73, p. 142–156, https://doi.org/10.1016/j.apgeochem.2016.08.006.

Moran, S.C., Freymueller, J.T., LaHusen, R.G., McGee, K.A., Poland, M.P., Power, J.A., Schmidt, D.A., Schneider, D.J., Stephens, G., Werner, C.A., and White, R.A., 2008, Instrumentation recommendations for volcano monitoring at U.S. volcanoes under the National Volcano Early Warning System: U.S. Geological Survey Scientific Investigations Report 2008–5114, 47 p., https://doi.org/10.3133/sir20085114.

Nadeau, P. A., Diefenbach, A.K., Hurwitz, S., and Swanson, D.A., 2020, From lava to water—A new era at Kīlauea: Eos, v. 101, https://doi.org/10.1029/2020EO149557.

National Academies of Sciences, Engineering, and Medicine, 2017, Volcanic eruptions and their repose, unrest, precursors, and timing: The National Academies Press, Washington, D.C., 134 p., https://doi.org/10.17226/24650.

Newhall, C.G., Albano, S.E., Matsumoto, N., and Sandoval, T., 2001, Roles of groundwater in volcanic unrest: Journal of the Geological Society of the Philippines, v. 56, p. 69–84.

Ohsawa, S., Saito, T., Yoshikawa, S., Mawatari, H., Yamada, M., Amita, K., Takamatsu, N., Sudo, Y., and Kagiyama, T., 2010, Color change of lake water at the active crater lake of Aso volcano, Yudamari, Japan—Is it in response to change in water quality induced by volcanic activity?: Limnology, v. 11, p. 207–215, https://doi.org/10.1007/s10201-009-0304-6.

Ono, T., Mori, T., and Tsunomori, F., 2020, High-frequency field auto-sampling of volcanic waters discharged near craters of active volcanoes: Bulletin of Volcanology, v. 82, no. 2, p. 1–15, https://doi.org/10.1007/s00445-020-1357-y.

Orr, T.R., Dietterich, H.R., and Poland, M.P., 2024, Tracking surface changes caused by volcanic activity, chap. G *of* Flinders, A.F., Lowenstern, J.B., Coombs, M.L., and Poland, M.P., eds., Recommended capabilities and instrumentation for volcano monitoring in the United States: U.S. Geological Survey Scientific Investigations Report 2024–5062–G, 11 p., https://doi.org/10.3133/sir20245062g.

Pasternack, G.B., and Varekamp, J.C., 1997, Volcanic lake systematics —I. Physical constraints: Bulletin of Volcanology, v. 58, p. 528–538, https://doi.org/10.1007/s004450050160.

Patrick, M.R., Orr, T., Antolik, L., Lee, L., and Kamibayashi, K., 2014, Continuous monitoring of Hawaiian volcanoes with thermal cameras: Journal of Applied Volcanology, v. 3, no 1., p. 1-19, https://doi.org/10.1186/2191-5040-3-1.

Rouwet, D., Christenson, B., Tassi, F., and Vandemeulebrouck, J., eds., 2015, Volcanic lakes: Springer-Verlag, Berlin, Heidelberg, 533 p., https://doi.org/10.1007/978-3-642-36833-2.

Rouwet, D., Sandri, L., Marzocchi, W., Gottsmann, J., Selva, J., Tonini, R., and Papale, P., 2014, Recognizing and tracking volcanic hazards related to non-magmatic unrest—A review: Journal of Applied Volcanology, v. 3, no. 17, https://doi.org/10.1186/s13617-014-0017-3.

Schaefer, J.R., Scott, W.E., Evans, W.C., Jorgenson, J., McGimsey, R.G., and Wang, B., 2008, The 2005 catastrophic acid crater lake drainage, lahar, and acidic aerosol formation at Mount Chiginagak volcano, Alaska, USA—Field observations and preliminary water and vegetation chemistry results: Geochemistry, Geophysics, Geosystems, v. 9, no. 7, https://doi.org/10.1029/2007GC001900.

Smalls, P.T., Sohn, R.A., and Collins, J.A., 2019, Lake-bottom seismograph observations of microseisms in Yellowstone Lake: Seismological Research Letters, v. 90, p. 1200–1208, https://doi.org/10.1785/0220180242.

Sohn, R., Harris, R., Linder, C., Luttrell, K., Lovalvo, D., Morgan, L., Seyfried, W., and Shanks, P., 2017, Exploring the restless floor of Yellowstone Lake: Eos, v. 98, https://doi.org/10.1029/2017EO087035.

Sparks, R.S.J., 2003, Forecasting volcanic eruptions: Earth and Planetary Science Letters, v. 210, nos. 1–2, p. 1–15, https://doi.org/10.1016/S0012-821X(03)00124-9.

Terada, A., Morita, Y., Hashimoto, T., Mori, T., Ohba, T., Yaguchi, M., and Kanda, W., 2018, Water sampling using a drone at Yugama crater lake, Kusatsu-Shirane volcano, Japan: Earth, Planets and Space, v. 70, no. 64, https://doi.org/10.1186/s40623-018-0835-3.

Thelen, W.A., Lyons, J.J., Iezzi, A.M., and Moran, S.C., 2024, Monitoring lahars and debris flows, chap. H *of* Flinders, A.F., Lowenstern, J.B., Coombs, M.L., and Poland, M.P., eds., Recommended capabilities and instrumentation for volcano monitoring in the United States: U.S. Geological Survey Scientific Investigations Report 2024–5062–H, 6 p., https://doi.org/10.3133/sir20245062h.

U.S. Geological Survey [USGS], 2024, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed April 15, 2024, at https://doi.org/10.5066/F7P55KJN.

Vandemeulebrouck, J., Sabroux, J.C., Halbwachs, M., Poussielgue, N., Grangeon, J., and Tabbagh, J., 2000, Hydroacoustic noise precursors of the 1990 eruption of Kelut Volcano, Indonesia: Journal of Volcanology and Geothermal Research, v. 97, nos. 1–4, p. 443–456, https://doi.org/10.1016/S0377-0273(99)00176-6.

Varekamp, J.C., 2015, The chemical composition and evolution of volcanic lakes, *in* Rouwet, D., Christenson, B., Tassi, F., Vandemeulebrouck, J., eds., Volcanic Lakes: Springer, Berlin, Heidelberg, p. 93–123, https://doi.org/10.1007/978-3-642-36833-2_4.

Waythomas, C.F., 2022, Selected crater and small caldera lakes in Alaska—Characteristics and hazards: Frontiers in Earth Science, v. 9, https://doi.org/10.3389/feart.2021.751216.

Werner, C., Evans, W.C., Kelly, P.J., McGimsey, R., Pfeffer, M., Doukas, M., and Neal, C., 2012, Deep magmatic degassing versus scrubbing—Elevated CO_2 emissions and C/S in the lead-up to the 2009 eruption of Redoubt Volcano, Alaska: Geochemistry, Geophysics, Geosystems, v. 13, no. 3, https://doi.org/10.1029/2011GC003794.

White, R., and McCausland, W., 2016, Volcano-tectonic earthquakes—A new tool for estimating intrusive volumes and forecasting eruptions: Journal of Volcanology and Geothermal Research, v. 309, p. 139–155, https://doi.org/10.1016/j.jvolgeores.2015.10.020.

Worni, R., Huggel, C., Stoffel, M., and Pulgarin, B., 2011, Challenges of modeling current very large lahars at Nevado del Huila Volcano, Colombia: Bulletin of Volcanology, v. 74, p. 309–324, https://doi.org/10.1007/s00445-011-0522-8.

Yamaoka, K., Geshi, N., Hashimoto, T., Ingebritsen, S.E., and Oikawa, T., 2016, Special issue “The phreatic eruption of Mt. Ontake volcano in 2014”: Earth, Planets and Space, v. 68, no. 175, https://doi.org/10.1186/s40623-016-0548-4.

Zimanowski, B., Büttner, R., Dellino, P., White, J.D.L., and Wohletz, K.H., 2015, Magma-water interaction and phreatomagmatic fragmentation, chap. 26 *of* Sigurdsson, H., Houghton, B.F., McNutt, S.R., Rymer, H., and Stix, J., eds, The Encyclopedia of Volcanoes: San Diego, Academic Press, p. 473–484, https://doi.org/10.1016/B978-0-12-385938-9.00026-2.

Moffett Field Publishing Service Center, California
Manuscript approved July 10, 2024
Edited by Linda Rogers and Monica Erdman
Layout and design by Cory Hurd

Ingebritsen and Hurwitz—**Streams, Springs, and Volcanic Lakes for Volcano Monitoring**—Scientific Investigations Report 2024–5062–F

ISSN 2328-031X (print)
ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20245062f