Drone Systems
and Applications

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Drone monitoring of volcanic lakes in Costa Rica: a new approach

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Abstract

For the first time ever, samples were collected from volcanic lake waters in Costa Rica using an unmanned aerial vehicle (drone), which represents a major achievement in human–machine interaction and innovation in the technology sector. A Matrice 600 Pro drone was used for remote sampling in the hyperacid crater lake of the Poás volcano, the mildly acidic Lake Botos, and the nearly neutral Lake Hule. A bailer bottle of 250 mL and a HOBO temperature probe, mounted on the drone, were deployed using a specially designed delivery retrieval system. A comparison was carried out relating to the geochemistry of lake water collected by drone as opposed to the hand-collected samples. The $SO_4{}^{-2}$/Cl ratios of the two samples at Poás hyperacid crater lake were similar, (1.1 ± 0.2) on average, an indication of a lake with homogenous water composition. The Lake Hule showed a similar composition to that registered 20 years ago. The waters from Lake Botos showed some differences, which may be explained by the influence of springs at the bottom of the lake, but the Wilcoxon's signed-rank test showed a good exhibit of a satisfactory level of similarity. Autonomous navigation proves to be very useful for faster, more efficient, reliable, and less hazardous sampling of volcanic lakes.

Key words: volcanic lake, Poás, drone water sampling, hyperacid lake, volcano monitoring, Matrice 600 Pro

Introduction

The Poás volcano is part of a complex stratovolcano structure located in the central mountain range of Costa Rica, 35 km NE of San José, the capital. The Poás complex is consisted of two cones with craters that host acidic volcanic lakes, Botos (2708 m above sea level, asl) and the main crater, the latter being a hyperacid, hot lake (Tassi et al. 2009*b*; Cabassi et al. 2014; SINAC 2020). Volcanic lakes are peculiar natural systems on Earth found in active volcanic systems. They are present in 476 volcanic structures worldwide (Cabassi et al. 2014; Rouwet et al. 2019) and classified as (a) highly active lakes, which are affected by the addition of significant amounts of heat and hyperacid magmatic–hydrothermal fluids, such as the main crater of Poás volcano and (b) low-activity lakes, that are characterized by carbon dioxide (CO_2) fluids, mainly at a relatively low discharge rate from sublacustrine fluids, facilitating the existence of stable vertical stratification and the build-up of large amounts of dissolved gases in the lake's deeper water layers. In this way, a lake overturn caused by external events, such as earthquakes, landslides, extreme climate conditions, or progressive gas build-up, can trigger the abrupt release of clouds of toxic gas into the atmosphere, hence putting communities and natural resources at risk.

Lakes with low volcanic activity are commonly called Nyos-type lakes, a classification under which both Lake Botos and Lake Hule fall (Pasternack and Varekamp 1997; Tassi et al. 2009*b*; Cabassi et al. 2014; Rouwet et al. 2016). The psychochemical characteristics of crater lakes enable the monitoring and forecasting of volcanic activity in active or dormant systems (Rowe et al. 1992; Christenson 2000; Anzidei et al. 2008; Tassi et al. 2009*a*).

Changes in volcanic water odor in Lake Botos, Lake Hule, and Lake Río Cuarto and fauna deaths suggest the occurrence of episodes linked to deep-source gas inflows (Umaña 2001). Renewal of lakes on the surface produces the so-called "limnic eruptions", such as those reported in the Mimony and Nyos lakes, in Cameroon, in 1984 and 1986, respectively (Sigurdsson et al. 1987; Evans et al. 1993, 1994). Likewise, hot crater lakes in active volcanoes overlap magmatic–hydrothermal systems, and water temperature can exhibit changes in response to volcanic activity (Brown et al. 1989; Hurst et al. 1991).

Continuous monitoring of crater lakes, specifically hot crater lakes, provide the necessary inputs for observing volcanic systems (Martinez et al. 2000; Ohba et al. 2008; Shinohara et al. 2015; Rouwet et al. 2016). These surveys can generate data about temporary chemical changes in the lake water, which is useful for identifying and predicting volcanic activity, such as phreatic and phreatomagmatic eruptions (Mastin and Witter 2000; Schaefer et al. 2008; Morrissey et al. 2010).

Manual sampling of crater lakes with geological structures, such as the Poás volcano, is difficult due to terrain conditions and the inherent risk of exposure to a volcanic eruption. Thus, drone sampling remains a critical application of drones in volcanology.

Drones have been used, primarily, in the sensing and sampling of gaseous volcanic components of the Poás volcano, as reported in studies by McGonigle et al. (2008); Shinohara (2013); Mori et al. (2016); Stix et al. (2018); Granados Bolaños et al. (2021). In addition, Rüdiger et al. (2017) used drones for similar purposes at the Turrialba and Masaya volcanoes in Costa Rica and Nicaragua, between 2016 and 2017.

Research by Stix et al. (2018) revealed that differential optical absorption spectrometer transects acquired by a drone provide a highly flexible and robust method to accurately measure fluxes of sulfur dioxide (SO_2), and that measurements of gas concentrations and proportions generate results comparable to ground surveying, in terms of accuracy and precision. The use of drones enables the rapid completion of transects beneath the dynamic column, by reducing overall sampling time when compared to on-foot surveys. This time saved is crucial, as gas plumes may be prone to changes in their direction or intensity, during the sampling process. Drones can easily access difficult terrain, which may be steep or unstable, thus making measurements possible in hard-to-reach areas subject to falling rocks or landslides, for instance. The trajectory of drones can be easily adjusted to account for the fluctuations in direction and intensity commonly observed when studying volcanic gas plumes, as described in studies by Stix et al. (2018) and James et al. (2020).

Other uses include monitoring of ground surface temperature, as noted by Harvey et al. (2016), Nishar et al. (2016), Chio and Lin (2017); magnetic field by Hashimoto et al. (2014); and 3D modeling of the terrain around the active crater by Westoby et al. (2012) and Moussallam et al. (2016). Moreover, McGonigle et al. (2008), Shinohara (2013), Gomez and Purdie (2016), Mori et al. (2016), D'Arcy et al. (2018), Stix et al. (2018), and Liu et al. (2020) have provided evidence as regards the use of drones to measure the components in volcanic gas and water sampling.

Terada et al. (2018) conducted water sampling in Japan's Yugama crater lake, facilitated by a drone launched from 2 km north of the lake's center. This drone had the capability to transport multiple bottles simultaneously, which enabled the sampling of water at different depths within the crater lake. This approach presents a significant advantage over the manual sampling method.

Despite operating under extreme conditions, such as high temperatures and hyperacidic lakes, no mechanical issues were reported during the sampling process. This could be explained by the bottle being suspended during the sampling at a distance of approximately 30 m below the drone. The samples were collected within the first meter of water below the surface, but the specific depths of the samples are unknown. Nonetheless, there are limitations to this method, such as wind speed (less than 8 m/s) and the need to carry out preliminary test flights for the adjustment of the passage points from the sampling equipment location to the lake, the mass of the payload, and the length of the cord used (Terada et al. 2018). More recently, Nadeau et al. (2020) completed some drone-aided measurements of the newly formed crater lake of the Kīlauea volcano in Hawaii. After the 2018 eruption of Kīlauea, they were in need of a drone to measure sulfate (SO_2 dissolving in water) and chloride ion concentrations in the water (Nadeau et al. 2020). Shingubara et al. (2021) have performed drone measurements in Kirishima (Iwo-yama) volcano and Aso volcaNo. They developed a drone-borne volcanic plume sampler and demonstrated that hydrogen's isotope δ^2H of hydrogen molecule (H_2) can be estimated remotely, in fumarolic gas and the fumarole outlet temperature based on δ^2H of H_2, at an apparent equilibrium temperature. Thus, this work is intended to provide evidence of the first drone-assisted sampling experience in Costa Rican volcanic crater lakes, and support future studies where this technique may be considered as a monitoring tool and a standard sampling method on an international scale.

Materials and methods

Drone flights were performed in three volcanic regions in Costa Rica, namely, three flights on the Poás hyperacid crater lake, two on Lake Botos, and one on Lake Hule (Table 1), located in the province of Alajuela (Fig. 1). The drone flights took place in summer 2021 and 2022 and were successfully completed, with no issues, at only one sampling site of each lake with 250 mL each time, marking the first time ever that this methodology and technique were used in Latin America. The DJI Matrice 600 Pro was used to obtain water samples from each lake, using DJI Go 4.0 system (version 3.0.2.0) and a tablet. The drone was equipped with a bailer bottle-sampling device made of high-density polyethylene, with a volume capacity of 250 mL. The bailer bottle consists of a tube that allows water to flow through it when lowered into a lake (Fig. 2). The water sample was collected this way near the surface (at a distance of less than 0.3 m). A different bailer bottle was used for each lake to avoid cross contamination between sampling sites. After each sampling, the bailer bottle was washed with soap and water, and subsequently cleaned with distilled water to eliminate any ions and odors.

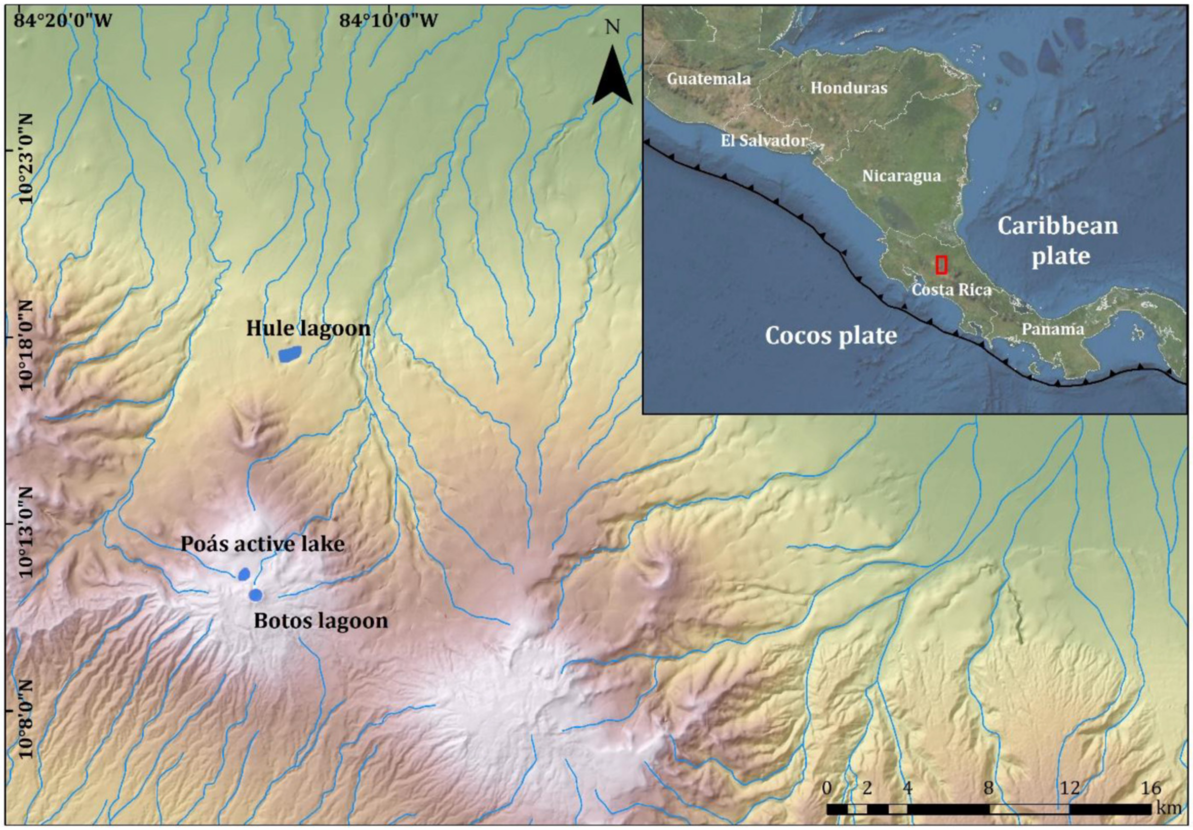
A small motor (Fig. 3), remotely operated, is used to take the bottle 30 m downwards, with a polyester rope from the drone to the lake, and then collect the water. When the bottle carrying the water sample is pulled upwards (Fig. 2), two bailer balls in the bottle close the water inlets and flow into the bottle stoppers, trapping the sampled water. The motor ascends the rope and gets the bottle with the water sample closer to the drone. For a safer return flight, the maximum sampling duration was about 20 min, with a payload weight of 1 kg, but the drone can handle a total weight of 5 kg. The

Table 1. Coordinates of the lakes sampled plus horizontal and vertical flight distances.

Lake	Coordinates of the sampling sites	Lake depth (m) maximum	Horizontal flight distance (m)	Vertical flight distance (m)
Poás hyperacid lake (Fig. 4*a*)	10°11′46.96″N 84°13′50.54″W	35[1]	629	250
Lake Botos (Fig. 4*b*)	10°11′15.88″N 84°13′39.95″W	9[2]	170	22
Lake Hule (Fig. 4*c*)	10°17′44.86″N 84°12′26.92″W	23[3]	500	144

[1] Cluzan (2021), personal conversation.
[2] Umaña (2001).
[3] Cabassi et al. (2014).

Fig. 1. Location and topography of the Poás hyperacid lake, Lake Botos, and Lake Hule, Alajuela, Costa Rica. This figure is plotted with Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS user community.



drone is equipped with a Zenmuse Z30 camera. Its propellers are made of carbon fiber, protecting the equipment from corrosion and erosion from acid aerosol conditions. Each flight was carried out at a maximum altitude of 20 m, and then remaining most of the time below the takeoff location altitude due to a descent into the volcanic crater. The drone was flown by staff from the Atmospheric Chemistry Laboratory (LAQAT-UNA) (pilot: JPSB) and the Costa Rican Volcanic and Seismic Observatory (OVSICORI-UNA) at Universidad Nacional (UNA). Drone speed before the sampling did not exceed 16 m/s, whereas the descent/ascent speed was approximately 2 m/s, and did not exceed 7 m/s afterwards.

To ensure successful drone flights, favorable weather conditions and good visibility are essential, and the same applies to the absence of rain, wind, or fog in the area. In this region, trade winds are another climatic factor where monitoring is necessary. The drone requires at least 4 m^2 of space clearance for takeoff and landing. The drone flight preparation can be completed within 20 min.

There was only one flight on each sampling site. At the Poás Volcano National Park, the takeoff location was at the tourist viewpoint of the hyperacid lake, from 629 m. The takeoff location at the Lake Botos was at the lake viewpoint, from a distance of 170 m, whereas the takeoff at Lake Hule took place

Fig. 2. Schematic illustrations of the bailer bottle filled up with the sampled water. Figures made by JPSB.

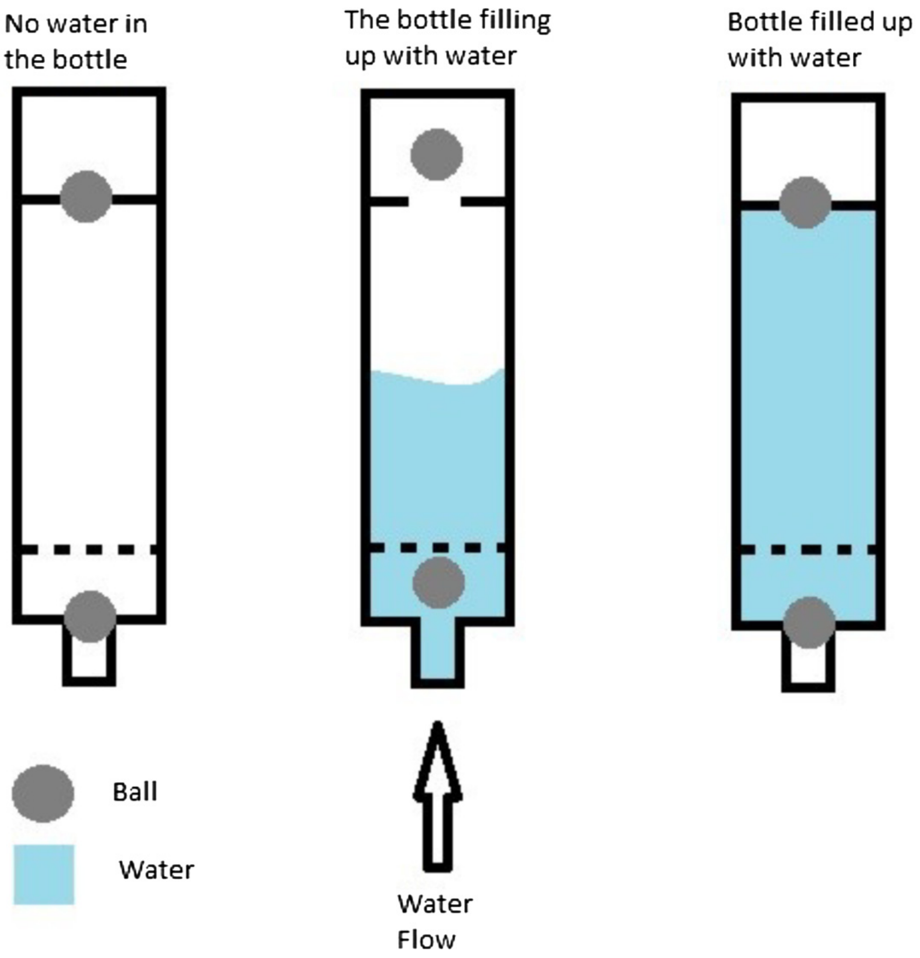


Fig. 3. (*a*) DJI Matrice 600 Pro drone used at sampling, (*b*) adjusted motor with 30 m rope, and (*c*) drone landing. Photographs taken by MMC.

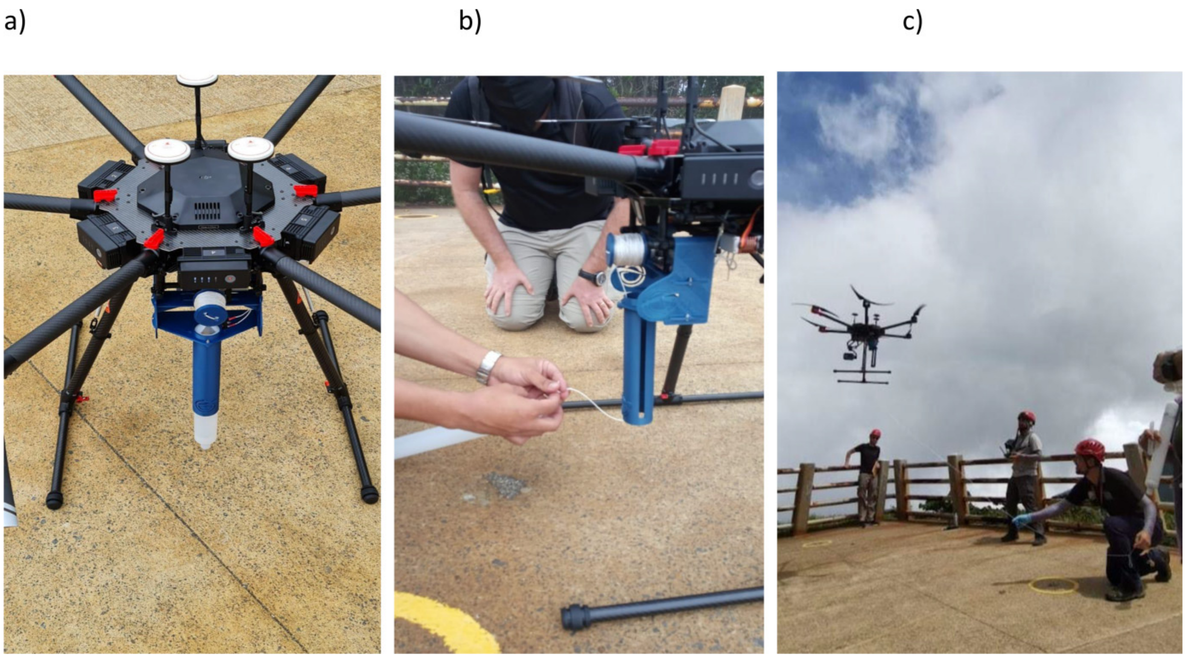
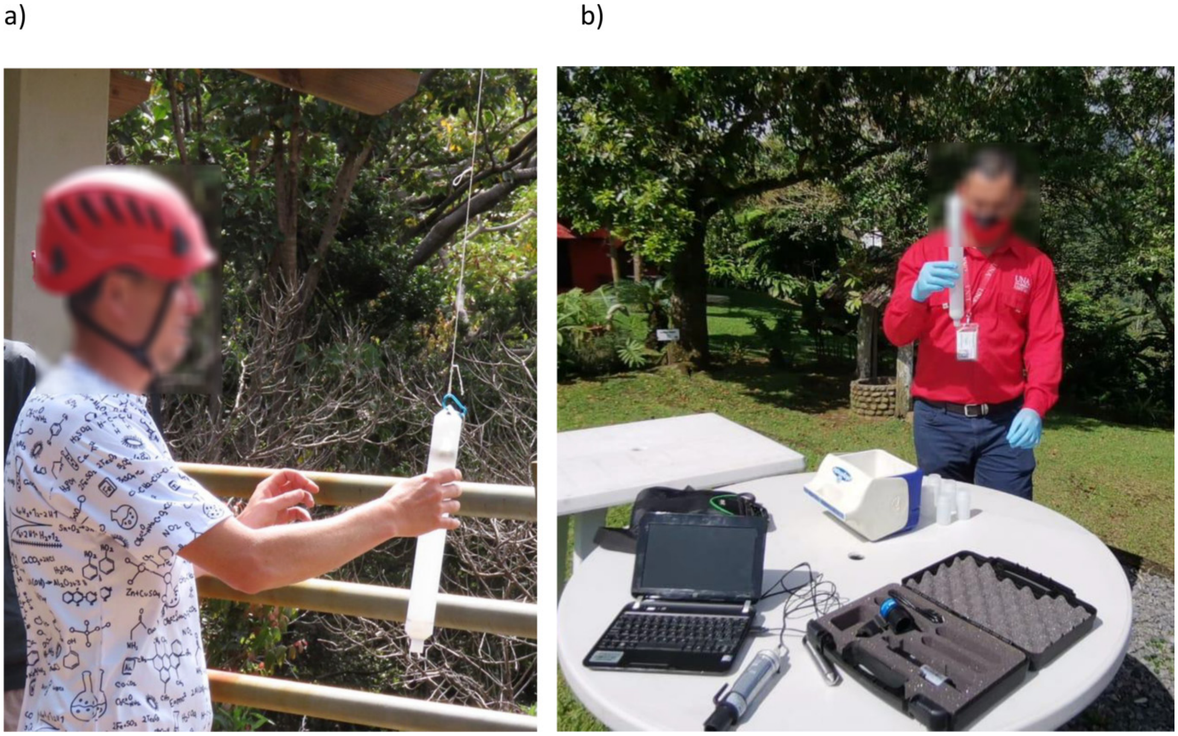


Fig. 4. Photographs of the three volcanic crater lakes sampled in the province of Alajuela, Costa Rica. (*a*) Poás Hyperacidic Lake, (*b*) Lake Botos, and (*c*) Lake Hule. Photographs (*a*) and (*c*) taken by MMC and photograph (*b*) taken by JPSB.

near the restaurant, at the edge of the Bosque Alegre Caldera, at a distance of 500 m (Fig. 4).

The water-sampling bottle was equipped with a waterproof HOBO to measure temperature. It consists of a 3 × 4 cm data logger, renders 12-bit resolution, and has ±0.2 °C accuracy. The pH, temperature, onductivity, total dissolved solids (TDS), dissolved oxygen (DO), and oxidation-reduction potential (ORP) parameters were measured on-site using a Hanna

Fig. 5. Bailer bottle drone sampling and in situ water measurement. Photographs taken by MMC of (*a*) MCL and (*b*) DUC receiving the bottle.



multiparameter HI 9829 m, following the sampling drone landing (Fig. 5*a*). After each flight survey, the water samples were taken to the laboratory for cation and anion analysis. This analysis was performed using a ThermoScientific ion chromatography ICS 5000+ (Sunnyvale, CA, USA), equipped with an auto sampler and a double column that uses a suppressed electrical conductivity detector. The manual sampling took place the same day of flight at each crater lake, on the side of the lake where terrain conditions were favorable for the scientists. The same procedure, equipment, and analysis were used for the samples taken manually.

Drone flight routes at the Poás crater lake, Lake Botos, and Lake Hule are shown in Fig. 6.

Results and discussion

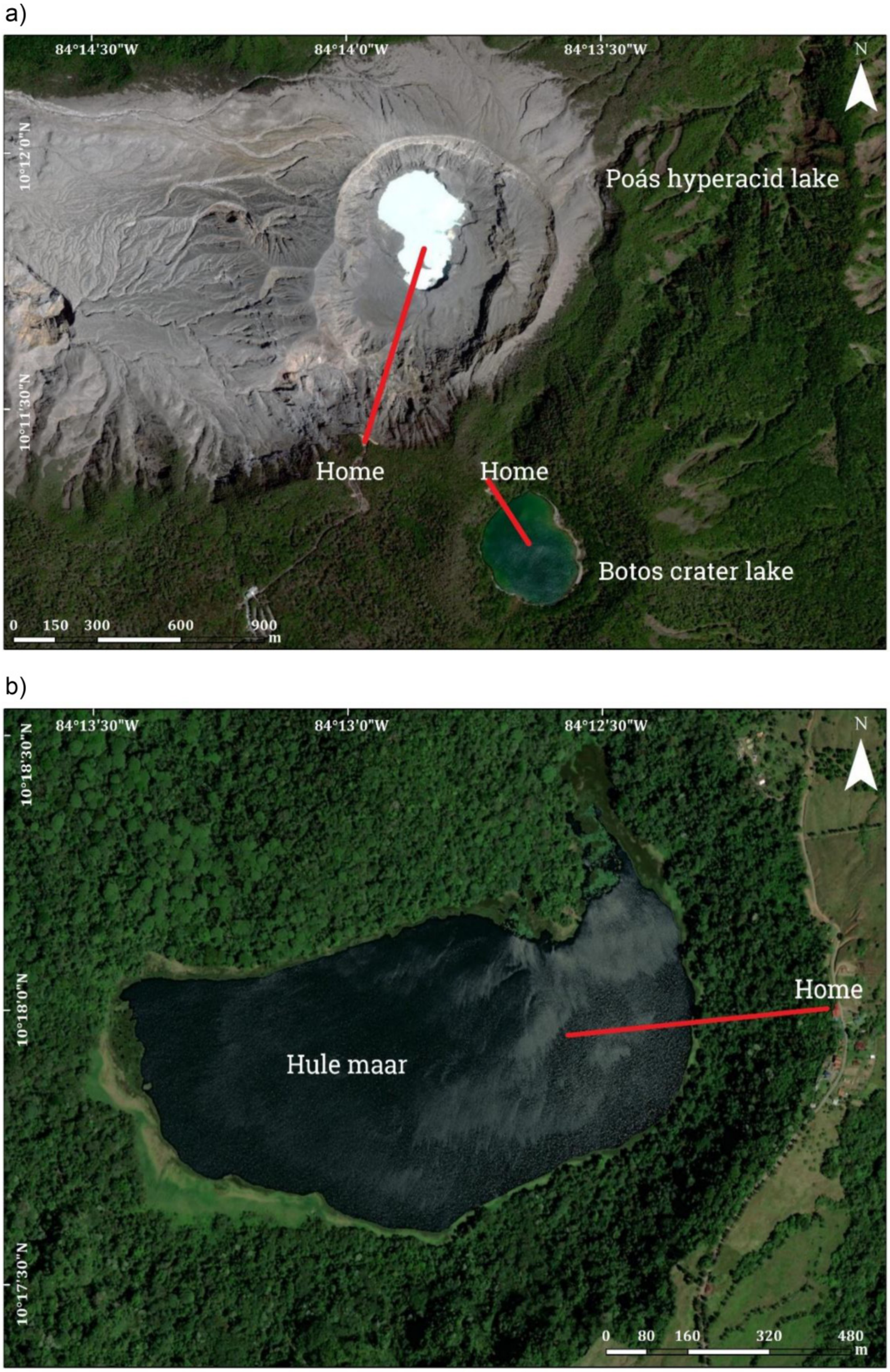
Lessons learned

The drone sampling carried out in the volcanic crater lakes was successful in less than 20 min of operation time, with the drone getting 250 mL samples of fresh water from each lake.

No issues were experienced during the drone flights as related to wind or drone transmission. Favorable weather conditions facilitated the drone sampling, namely, sunny days and high clouds. Sampling was also made possible by the absence of rain or high wind speed (at less than 8 m/s), few clouds (only cirrus clouds above 5 km), and good visibility within a distance of more than 2 km. These are necessary conditions for successful drone flying, as much as good stability of the equipment and the water bottle. High wind conditions could generate issues with the drone operation, putting the landing at risk, and therefore compromising a successful water sampling campaign. To avoid any problems, a reconnaissance drone flight of the surrounding area, prior to the water sampling, is recommended for measuring the lake's horizontal and vertical distances (i.e., relative height from takeoff site to lake surface level). This initial flight could also provide information regarding the meteorological conditions of the sampling zone or help identify any potential signal loss issues that may arise during the subsequent flights. Furthermore, two people are required for a successful operation, one pilot and a visual observer with binoculars, to assist in the flying of the drone flight and collecting the bottle in case of battery problems at landing. A third person (optional) may also be able to assist the pilot in ensuring the safe and successful completion of the flight, if the visual observer is busy addressing payload issues.

The presence of fumaroles and acid fumes in the Poás hyperacid lake could represent a problem for drones since acid aerosols could degrade their electrical system and (or) connectivity of the antennas. To avoid these situations, the drone could be flown around the fumaroles, so it is not affected by acid gases and aerosols. Mori et al. (2016) measured volcanic gas emissions at Mt. Ontake volcano in Japan, testing for SO_2 and H_2S using a drone. They provided details on the risk of flying a drone through a huge gas plume, in situations where the drone can be affected by the gases. Furthermore, they recommended flying drones and taking measurements with relatively small-sized plumes. As for the measurements conducted in Costa Rica, the LAQAT/OVSICORI personnel followed the recommendations to ensure that the drone was protected against the damaging effects of acid conditions.

Fig. 6. Flight routes (red lines) at (*a*) Poás hyperacid lake and Lake Botos, and (*b*) Lake Hule. This figure is plotted with Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS user community.



Ash can have a direct impact on the drone flight operations, camera, and electrical components, potentially resulting in a failure of the return to home function. It is also important to recognize that the duration of a single flight is comparatively shorter at crater lakes situated at high altitudes, due to the lower density of the ambient air. Therefore, it is imperative to consider this before drone takeoffs at high-altitude sampling sites.

No issues were experienced with the drone because of acid conditions, or moderately high temperature of the lake, which was around 40 °C. Use of the motor with the bottle attached to a 30 m length rope made it possible to protect the drone from the harsh conditions near the lake surface, while also enabling safe and appropriate retrieval of the water sample at an operational range. Thus, the use of a rope allows the drone to approach the lake surface. The recommendations outlined in Terada et al. (2018) and Nadeau et al. (2020) were of significant value, especially when determining the appropriate rope length to ensure safe drone flight conditions and the potential risks associated with unfavorable weather conditions for drone flying.

A strong signal for the drone camera feed is also important, as the use of the camera feed may make it possible to know the meteorological conditions and morphology of the lake, thus allowing the drone to be potentially switched from a programmed flight into a manual flight for sampling purposes, even if a satellite signal is unavailable. To mitigate the risk of a drone crash, it is recommended to select a sampling site that is situated at a reasonable distance from the walls of the crater, as katabatic wind can pose a significant threat. The descending velocity of the drone to the lake should be slow (around than 2 m/s), to avoid a pendulum movement of the bottle leading to instability. Both total weight and oscillation of the bottle place increased requirements on the energy consumption of the drone batteries. The mass of the payload and the times that the rope goes up and down with the bottle will decrease the battery duration. Therefore, the person who operates the drone should monitor the battery carefully throughout each flight. The lakes sampled are typically situated in deep, steep-walled craters. To ensure successful sampling while maintaining safety, some manual adjustments may be required, often guided by an observer equipped with binoculars who provides critical information (in certain countries, the use of binoculars by the visual observer would classify the operation as Beyond Visual Line of Sight). This information should be added, as it has significant implications in terms of regulatory compliance. These safety measurements are crucial in surveying volcanic lakes by drone. Liu et al. (2020) explained that the risk scenario of Manam volcano and other volcanoes is unique for each flight and is something to consider during the planning of the operation and before every sampling.

The ideal approach is to retract the sample bottle back to the bottle transport system (i.e., the blue enclosure in Fig. 3*a*) before landing. This process would help ensure that the bottle is protected against potential collisions with the ground or other objects during the landing. In comparison, the other approach mentioned later involves hovering the drone in the air, retrieving the sampling bottle while still hanging at the end of the fully extended rope, and then rewinding the rope before landing. This is the best procedure, but it depends on the battery charge remaining during the landing as rewinding of the rope could consume roughly 15%–20% of battery. This procedure protects the bottle from crashing into the soil or colliding at ground level while landing. Local wind conditions could generate issues with slow drone movements at the landing site. Another option for landing and getting the water sample first is to receive the sampling bottle with the extended rope and hover the drone in the air. After this, water can be drained into the two bottles previously cleaned at the laboratory with distilled water. One bottle is for in situ analysis and the second one is for the laboratory analysis. After this procedure, the rope is collected to the water-sampling payload, allowing for proper landing, which should be done in a precise manner and small drone movements to prevent crashes or sample spills.

In general, this sampling technique aided by a drone is very effective because of considerably shorter sample collecting times, enabling the scientist to analyze fresh water in less than 20 minutes, and thus proving to be a very useful method for studying the actual situation of the lake. In the case of the Poás hyperacid lake, for example, the manual sampling method can take around 4 h, whereas sampling at Lake Botos and Lake Hule could take between 30 min and up to an hour. Additionally, unlike the manual sampling method, which typically involves taking water from one side of each lake, the drone method enables water to be sampled from the main subaquatic vent of the Poás hyperacidic lake. This approach may reduce the dilution effect caused by rain and runoff water from the surrounding mountain. In the case of Lake Botos and Lake Hule, the drone method allowed for sampling in multiple locations within the center of the lake, whereas the manual method would require a scientist to use a kayak or small boat to sample the same locations, which could take up to 5 h. Another important advantage of sampling with drones is the reduced risk of exposure to acid gases and aerosols compared to manual sampling at the side of the crater lake. With manual sampling, the scientist must walk into dangerous terrain, with cracks in the ground and rocks that can break away from the crater walls. In addition, concentrations of SO_2, H_2S, and acid aerosols could pose a health risk to scientists conducting the measurements. This is a great example of how drone applications benefit volcanologists. Now, however, the drone sampling technique has its advantages; it is unlikely to replace manual sampling due to several factors. These include the high initial investment, the need for proficient staff to handle the drone, the limited quantity of samples that can be obtained, and the limited flight time. It is important to stress that this is a reliable new option for volcanic monitoring despite these limitations and is another option for scientists to study the water crater lakes. D'Arcy et al. (2018) mentioned that drones are the perfect tool for volcanologists requiring to access these danger zones, and this is an idea that scientists in Costa Rica are trying to implement, making the study of volcanoes more effective and safer. There are more beneficial effects from this research, as in the case of SINAC Park Rangers tasked with managing the National Park system in Costa Rica, who now have more information to ponder when it comes to decision-making processes to enhance community safety. By implementing the drone technology, the risk of anyone happening to breathe acidic gases or aerosols is reduced significantly. The procedure and safety recommendations published by Terada et al. (2018) are important for future research in volcanoes, because of their sampling of the Yugama crater lake with a six-rotor LAB645 drone and a metal-free bottle made of high-density polyethylene. This procedure is the foundation for the drone measuring of volcanic crater lakes in Costa Rica as

Table 2. Physicochemical values of Poás hyperacid lake waters sampled with the drone Matrice 600 Pro and manually.

Parameter	Poás hyperacid lake[a] (9 June 2021)	Poás hyperacid crater lake[a] (31 August 2021)	Poás hyperacid crater lake[b] (22 August 2022)	Poás hyperacid crater lake[a] (22 August 2022)
F^- (mg/L)	718 ± 30	270 ± 10	188 ± 10	183 ± 10
Cl^- (mg/L)	16 905 ± 1680	8430 ± 128	9092 ± 140	10 447 ± 200
$SO_4{}^{-2}$ (mg/L)	19 504 ± 209	7909 ± 239	10 012 ± 200	11 756 ± 202
Li^+ (mg/L)	0.67 ± 0.04	0.06 ± 0.02	0.19 ± 0.03	0.15 ± 0.03
Na^+ (mg/L)	404 ± 20	353 ± 19	631 ± 22	798 ± 24
$NH_4{}^+$ (mg/L)	< DL = 0.03	< DL = 0.03	< DL = 0.03	< DL = 0.03
K^+ (mg/L)	79 ± 6	74 ± 5	67 ± 4	58 ± 4
Mg^{+2} (mg/L)	152 ± 14	321 ± 21	205 ± 17	202 ± 17
Ca^{+2} (mg/L)	828 ± 16	599 ± 13	681 ± 15	628 ± 14
pH ± 0.01	0.31	0.61	0.08	0.02
Temperature, ± 0.1 °C (with HOBO)	40.0	39.1	46.0	38.0
Conductivity, ± 0.1 mS/cm	165.0	145.0	144.7	132.0
TDS, ± 0.1 mg/L	82.6	66.3	72.4	66.0
DO, ± 0.01 mg/L	1.29	2.05	1.41	1.53
ORP, ± 0.1 mV	367.8	361.9±	365.6	444.0
$SO_4{}^{2-}/F^-$	27.2	29.2	53.2	64.2
$SO_4{}^{2-}/Cl^-$	1.15	0.93	1.10	1.12

Note: DL: detection limit. [a]Drone sampling at the central region of the lake.
[b]Manual sampling at the eastern edge of the lake.

Table 3. Physicochemical parameters of Lake Botos and Lake Hule water samples (drone and manually collected).

Parameter	Lake Botos[b] (10 September 2021)	Lake Botos[a] (10 September 2021)	Lake Botos[b] (26 October 2021)	Lake Botos[a] (26 October 2021)	Lake Botos[b] (11 December 2021)	Lake Botos[a] (11 December 2021)	Lake Hule[a] (July 2021)
F^- (mg/L)	0.113 ± 0.005	0.255 ± 0.005	0.112 ± 0.005	0.113 ± 0.005	0.089 ± 0.005	0.324 ± 0.005	0.09 ± 0.01
Cl^- (mg/L)	2.12 ± 0.02	8.51 ± 0.02	1.94 ± 0.02	2.04 ± 0.02	20.73 ± 0.02	2.81 ± 0.02	3.75 ± 0.02
$SO_4{}^{-2}$ (mg/L)	19.05 ± 0.03	26.63 ± 0.03	19.58 ± 0.03	19.32 ± 0.03	17.69 ± 0.03	17.66 ± 0.03	4.22 ± 0.03
Li^+ (mg/L)	< LD = 0.02	< LD = 0.02	< LD = 0.02	< LD = 0.02	< LD = 0.02	< LD = 0.02	0.03 ± 0.02
Na^+ (mg/L)	0.72 ± 0.05	1.05 ± 0.05	0.67 ± 0.05	0.72 ± 0.05	7.39 ± 0.05	1.23 ± 0.05	20.9 ± 0.5
$NH_4{}^+$ (mg/L)	< DL = 0.03	< DL = 0.03	< DL = 0.03	< DL = 0.03	< DL = 0.03	< DL = 0.03	0.98 ± 0.03
K^+ (mg/L)	0.24 ± 0.02	2.08 ± 0.02	0.31 ± 0.02	0.22 ± 0.02	8.72 ± 0.02	0.88 ± 0.02	2.56 ± 0.02
Mg^{+2} (mg/L)	0.68 ± 0.06	0.89 ± 0.06	0.69 ± 0.06	0.72 ± 0.06	< DL = 0.06	0.60 ± 0.06	2.34 ± 0.06
Ca^{+2} (mg/L)	3.36 ± 0.08	3.97 ± 0.08	3.51 ± 0.08	3.54 ± 0.08	3.24 ± 0.08	3.25 ± 0.08	7.7 ± 0.1
pH ± 0.01	3.95	3.90	3.98	3.99	3.94	4.11	6.97
Temperature, ± 0.1°C (with HOBO)	16.5	16.0	18.8	16.3	17.3	14.1	30.2
Conductivity, ± 0.1 µS/cm	75.0	109.0	163.0	168.0	209.0	382.0	76.0
TDS, ± 0.1 mg/L	36.0	54.0	82.0	82.0	107.0	194.0	38.0
DO, ± 0.01 mg/L	3.20	3.01	4.95	3.66	3.20	2.58	2.72
ORP, ± 0.1 mV	361.1	348.4	331.4	340.4	240.2	88.8	168.0

[a]Drone sampling.
[b]Manual sampling.

the Yugama crater lake has similar conditions to those of Poás volcano.

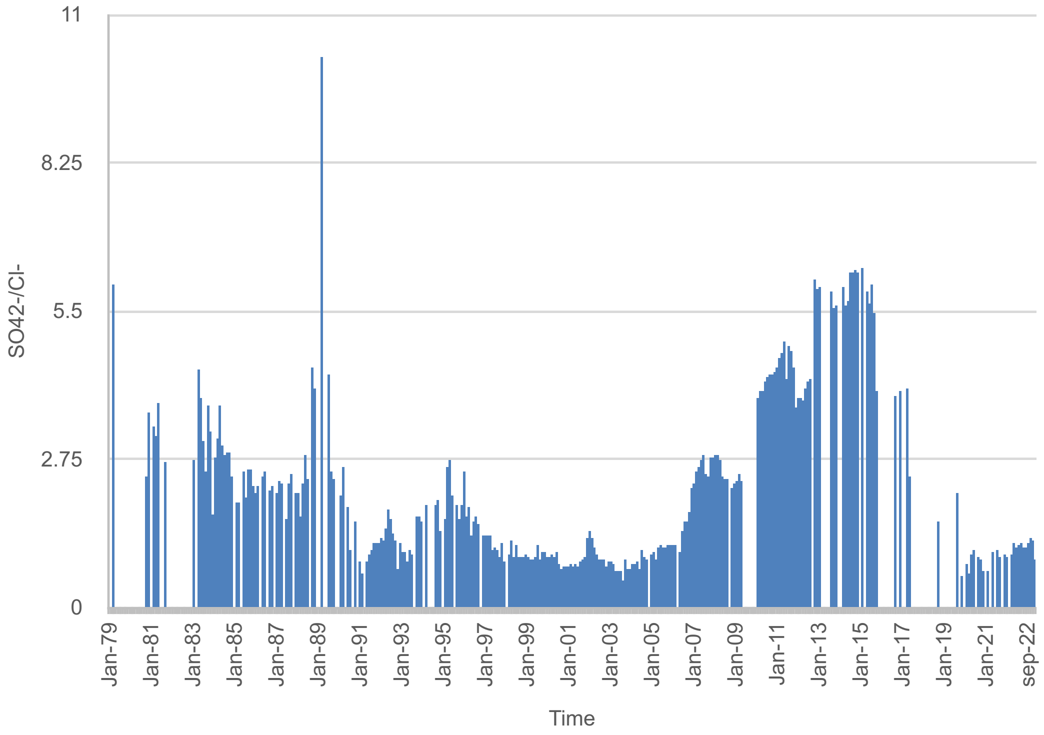
Analysis of volcanic lakes

The physicochemical data obtained from the water samples, using a drone or manually at the three volcanic sites, are shown in Tables 2 and 3.

Drone sampling at the Poás hyperacid lake took place in June and August 2021 and August 2022, with slight differences found in terms of the physicochemical values from the sampling campaigns. The samples were collected at the same site of the lake, near the remnants of the pyroclastic dome destroyed by the 2017 magmatic eruptions and is now a subaqueous fumarolic vent with vertical walls ("Boca A" or "La Isla"). The "Boca A" is the most important subaquatic vent within the hyperacid lake.

The August 2021 sample had a higher pH value and lower values for F^-, Cl^-, Br^-, $SO_4{}^{-2}$, Li^+, Na^+, and Ca^{+2} concentrations than the June 2021 sample. This can be attributed to the

Fig. 7. Binary diagram of SO_4^{2-}/Cl^- ratios, Poás hyperacid lake, collected from September 1978 to January 2023. Samples collected using a drone for the 2021–2023 period.



heavy rain events occurring in August, and leading to dilution and stratification of the lake water, lowering ion concentrations, and increased acidity. Temperature was virtually the same during the sampling dates of 2021 and 2022, at around 40 °C. As described in the literature, temperature is not a key parameter in relation to phreatic activity (Rouwet et al. 2016). For this reason, it is other parameters, such as F^-, Cl^-, SO_4^{-2}, Li^+, Na^+, Mg^{+2}, and Ca^{+2} that need to be measured for understanding the behavior and evolution of the Poás hyperacid lake and envisage potential eruptions (Rowe et al. 1992; Martínez 2008).

SO_4^{-2}/Cl^- ratios are a good parameter for monitoring changes in the chemistry of the lake–hydrothermal system since fresh magmatic intrusions at Poás volcano have been signaled by enhanced input of sulfur-rich gases into the lake, followed by an enrichment of the hydrothermal brines in chlorine (Martínez 2008).

From June 2021 to August 2022, the average SO_4^{-2}/Cl^- ratios of the Poás hyperacid lake were 1.1 (±0.2), irrespective of the sample collection method. This suggests that the lake maintained a similar composition over a 14-month period (see Fig. 7). These values match the ones recorded between the 1990s and 2005, a period of a fast lake volume growth accompanied with a decrease in the influx of sulfur volatiles, and an enrichment of the lake in chlorine (Martínez-Cruz et al. 2019; Rouwet et al. 2019). Furthermore, said SO_4^{-2}/Cl^- values help to validate the sampling from the hyperacid lake, near the Boca A vent, using a drone, and manually on the eastern edge of the lake.

A statistical analysis was conducted of samples taken on the same day in 2022, comparing measurements obtained with the drone to those taken manually at one side of the Poás hyperacidic lake. We used the relative percent difference (RPD) as defined by the US Environmental Protection Agency (1994),

$$\mathrm{RPD} = \frac{|S - D|}{\frac{(S+D)}{2}} \times 100$$

where S is the measured concentration from the drone sample and D is the measured concentration from the manual sample. This analysis revealed encouraging findings, particularly with sulfate and chlorine concentrations, showing a differential percentage of +16% and +14%, respectively. This acceptable difference is explained by the drone measurements being taken at the "Boca A" vent, the most active vent of the volcano, while the manual measurement was obtained at the east side of the crater, approximately 170 m away from "Boca A", where a dilution of the ions could occur. The pH values for the drone-collected sample were 0.02, and 0.08 for the sample collected manually. This could be caused by the "Boca A" vent constantly injecting sulfur gases, which are distributed into the lake. Moreover, with rainwater from the mountain draining into the crater, the dilution process in the shore is higher during Costa Rica's rainy season, between May and November of each year. The SO_4^{2-}/F^- factor measured for the drone sample was 64.2, and 53.2 for the manual sample. The SO_4^{2-}/Cl^- factor was 1.1 and 1.1, respectively. This means that the relation of sulfate with fluorine and sulfate with chlorine is the same.

As for Lake Botos, a comparison was also carried out between the drone sample and manual sample. Some differences between the two sampling sites were recorded, which

Table 4. Statistical results of the Wilcoxon's signed-rank test for the comparison between the Lake Botos samples (drone and manually collected).

Parameter	p value	Alpha value	Result
F^- (mg/L)	0.250	0.05	No significant difference
Cl^- (mg/L)	1.000	0.05	No significant difference
SO_4^{-2} (mg/L)	1.000	0.05	No significant difference
Na^+ (mg/L)	1.000	0.05	No significant difference
K^+ (mg/L)	0.750	0.05	No significant difference
Mg^{+2} (mg/L)	0.500	0.05	No significant difference
Ca^{+2} (mg/L)	0.500	0.05	No significant difference
pH ± 0.01	0.750	0.05	No significant difference
Temperature, ± 0.1 °C (with HOBO)	0.250	0.05	No significant difference
Conductivity, ± 0.1 µS/cm	0.250	0.05	No significant difference
TDS, ± 0.1 mg/L	0.500	0.05	No significant difference
DO, ± 0.01 mg/L	0.250	0.05	No significant difference
ORP, ± 0.1 mV	0.500	0.05	No significant difference

might respond to a possible release of bubbles or the influence of springs at the bottom or edges of the lake. This accounted for the drone-sampled site having a lower pH value, moderately higher ion concentrations, and a lower ORP (Horn and Haberyan 1993). These differences are difficult to explain because of the several days of heavy rains in Costa Rica, during August 2021, causing the crater lake level to rise and diluting the ion concentration because of runoff rainwater coming from the forested mountain around the lake and rainwater falling directly into the lake (Table 3). To achieve a better understanding of this variance, further investigation of the crater lake would be necessary. Lake Botos is presently acidic, with a pH around 3.90 due to the Cl-rich degassing from the 2017 eruption residual body of magma, still cooling down, and the atmospheric precipitation of acid aerosols.

It must be noted that between 1997 and 2021, the pH of Lake Botos showed a trend of consistent decrease, ranging from 5.90 down to 3.90 (OVSICORI-UNA, unpublished data). On the other hand, conductivity, temperature, and ion concentrations have shown increasing trends (from 45 to 65 µS/cm, from 13.0 to 16.3 °C, and SO_4^{2-} from 7.9 to 19.0 mg/L, respectively).

In addition, the Wilcoxon's signed-rank test, with a significance level of 95% and a sample size of $n = 3$, did not reveal any significant differences between the samples collected by the two methods. This finding supports the observed level of similarity between the drone and manual measurements of Lake Botos (Table 4). However, it is important to exercise caution when interpreting these results due to the small sample size, which may have limited statistical power to detect major differences.

From the foregoing, it follows that the lake is stable, and there is no evidence, at least at shallow depths, of significant changes or input of magmatic volatiles. Lake Hule does not currently pose an immediate risk to the people living in the surrounding area, and it can serve as a recreational park for activities, such as swimming, hiking, and kayaking.

The drone sampling methodology on these types of lakes is important because it represents a lower risk for the field-sampling staff and is faster than walking to each lake where manual sampling is necessary. The scientist could take the drone, by car, to the departure site of the crater. Furthermore, the methodology also enables for a better perspective when studying spatial variability of the volcanic system, highlighting how this approach helps us understand the main processes of physicochemical composition within the lake and some sites at the center of the crater lake. The use of drone measurements could also have a positive impact on the community and tourism, by providing an opportunity for people to learn about volcanoes and virtually experience visiting an active volcano in a safe and modern way. This methodology also creates an opportunity for synergy, with drone fight videos being made available to staff for observational analysis after the mission is completed.

The difference between the three lakes represents the variation of volcanic activity at each location. The Poás hyperacid lake has a plume of gas and occasional particulate matter emissions. Lake Botos could have bubbles produced at the bottom of the lake, near the center region, and an influence of the Poás hyperacid lake could generate wet and dry deposition over Lake Botos water.

Recommendations for Future Work

Through these experiences, the UNA team have set up a regular sampling of Costa Rica's volcanic lakes for the purposes of surveillance, hazard assessment, and research. The aim for this is to prepare a second drone for field surveys at inaccessible or dangerous sites and carry out in situ sample measurement of fumarolic gases, airborne particulates (aerosols and ashes) using light-weight gas, thermal sensors, and ash samplers. Finally, a submersible drone could be of great value for the study of degassing and geographical structures in mild-acidic to freshwater lakes, such as Botos, Hule, Río Cuarto, and others. Similarly, researchers can collect waypoint info and create a GPS database, including water chemistry records from previous crater lake samples for a matrix, which may help improve the volcanic forecasting system.

This drone technique could take water samples from volcanic places with hard-to-access terrain or inaccessible sites.

Additionally, a different procedure might be used, with samples taken at different sites of the lake, thus permitting scientists to study the physicochemical spatial variability and providing a different approach to the monitoring. Depending on flying distances, the drone could make the first sampling at the lake, return to the takeoff zone, drop the water bottle without landing, and then go back to another sampling place at the lake. With this procedure, a bigger volume of water sample and different characteristics of the lake could be examined. These flights could generate increasingly valuable information for park rangers, who might facilitate decision-making and management of natural resources.

Another use of drone could be the sampling of ash deposits, soil, sediments, and other materials in hazardous places or deep lakes. For this purpose, new equipment and a new option in the remote controller might be required.

Conclusion

The LAQAT/OVSICORI scientific team analyzed three volcanic lakes in Costa Rica and demonstrated the effectiveness of drone technology in sampling water, taking less than 20 min at each volcanic crater. This approach reduces exposure to volcanic gases and acid aerosols, making it a safer method for volcanology measurements. It also allows for sampling at the center of the crater or at the main vent, and can yield results comparable to manual measurements taken at one side of the lake. Our experiment has led to the development of a new procedure for sampling volcanic lakes, with a reduced risk to scientists and the ability to sample from different locations in each lake. However, further research is necessary to evaluate the full potential of this method and its implications for volcano monitoring and hazard assessment.

The sampling results showed consistency in terms of physicochemical parameter values, as compared to the historical data from the Poás hyperacid lake, e.g., the SO_4^{-2}/F^-, SO_4^{-2}/Cl^-, and Mg/Cl ratios. Manual sampling of crater lake water is difficult during volcanic unrest due to the probability of an eruption, rendering drone technology as an opportunity for the study of volcanoes in these conditions.

Samples from Lake Botos collected by both drone and manual methods showed no significant difference, as evidenced by the Wilcoxon's signed-rank test. This implies that utilizing drones is an effective approach for studying volcanology and crater lake activity.

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Data availability

Data generated or analyzed during this study are provided in full within the published article.

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Competing interests

The authors declare there are no competing interests.

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