Mapping topo-bathymetry of transparent tufa lakes using UAV-based photogrammetry and RGB imagery

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Seasonal or interannual precipitation differences lead to changes in the water level of a tufa lake, while the underwater topography affects its local depth. Therefore, topo-bathymetry is important to study and protect the aquatic environment of tufa lakes. However, traditional field-based topo-bathymetric surveying methods (e.g., sounding rod or sonar) inevitably disturb the fragile lake ecosystem. In recent years, the emerging remote sensing technology of unmanned aerial vehicles (UAV) has provided a cost-effective solution for measuring topo-bathymetry without disturbance. In this paper, taking Spark Lake in Jiuzhaigou, China, as an example, we captured red-green-blue (RGB) images using a fixed-wing UAV and produced a digital elevation model (DEM) prior to the Jiuzhaigou Earthquake using Structure-from-Motion (SfM) photogrammetry. The underwater topography of Spark Lake was obtained by refraction correction and water color inversion based on the DEM and orthophoto, respectively. For refraction correction, a water depth correction model based on Snell’s Law was used. For water color inversion, general band ratio models were replaced by a band difference model (blue band - green band). The qualities of the resulting DEMs produced by the two methods were evaluated against the topography of the drained Spark Lake after the earthquake, and the corresponding DEMs of difference (DoD) were also analyzed. The coefficient of determination ($R^2$) and root mean square error (RMSE) are 0.88 and 1.32 m for refraction correction, and 0.86 and 1.37 m for water color inversion, respectively. The results demonstrated the feasibility and effectiveness of applying UAV-acquired RGB imagery and the two optical remote sensing methods to topo-bathymetric mapping of transparent tufa lakes.

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\section{1. Introduction}

Tufa is localized precipitation of calcium carbonate (CaCO$_3$) generated by rivers, lakes, or springs in karst areas through the combined effect of physical, chemical, and biological actions (Liu, 2017). Tufa is widely distributed in the world (Ford and Pedley, 1996) and forms beautiful tufa lakes and waterfalls in some places, including Jiuzhaigou National Nature Reserve in China, Yosemite National Park in the United States, and Plitvice Lakes National Park in Croatia. The water of tufa lakes is usually clear and transparent because of very small amounts of impurities and minimal sediment transport. As tufa formation is a long geomorphic process (Florsheim et al., 2013), it is almost impossible to recover in a short time once destroyed. However, seasonal or interannual precipitation differences usually lead to changes in the water level of a tufa lake, while the underwater topography affects its local depth distribution. If the underwater topography is altered for certain reason, the local bathymetry will be influenced and the associated aquatic ecosystem has to adjust accordingly. Therefore, accurate and updated topo-bathymetric data is critical for studying and protecting the aquatic ecosystem (Profe et al., 2016).

We reviewed the possible data sources/technologies and assessed their fitness for mapping topo-bathymetry of tufa lakes. Primitive field-based surveying of topo-bathymetry is done with a sounding rod or a sounding hammer, which is an extremely time-consuming and heavy workload. Acoustic measurements (Giordano et al., 2015; Rogers et al., 2020) using a single beam sonar or a multiple beam sonar improves efficiency, but still inevitably brings serious disturbance to the fragile aquatic ecosystem by boats and sonars operating while immersed. As an active remote sensing technology, light detection and ranging (LiDAR) plays an increasingly important role in topographic survey and geomorphologic mapping. Meanwhile, airborne bathymetric LiDAR (Saylam et al., 2018) provides a non-contact method for measuring topo-bathymetry, but high purchase costs and heavy training requirements restrict its wide application. Furthermore, satellite remotely sensed data including Landsat-8 (Jagalingam et al., 2015), SPOT-5 (Poupardin et al., 2016), and Sentinel-2 (Casal et al., 2020) have been widely used for undisturbed bathymetric surveys of large...
areas near the coast, and many inversion models for water depth have been developed (Stumpf et al., 2003; Su et al., 2008). In addition, more and more attention has been paid to satellite derived bathymetry by two-media photogrammetry (Hodúl et al., 2018). But the relatively low spatial resolution makes satellite images poorly suited for small water areas like tufa lakes.

In recent years, with the advantages of low cost, flexible deployment, and hyper-spatial resolution, the new remote sensing technology of unmanned aerial vehicles (UAV) or drones has provided a promising solution for surveying the topo-bathymetry of small water areas (Colomina and Molina, 2014; Xiang et al., 2019). Before the emergence of civilian UAVs, Lejot et al. (2007) used light platforms and off-the-shelf cameras to map the water depth and underwater topography of a river channel. Existing UAV-based bathymetric models rely on two approaches, namely photogrammetry and spectral analysis. With the advent of Structure-from-Motion (SfM) techniques (Westoby et al., 2012) in the field of computer vision, high spatial resolution digital surface models (DSM) can be automatically produced from UAV-acquired overlapping optical images using SfM photogrammetry. Based on these new technologies, multiple studies of the potential for measuring topo-bathymetry by refraction correction based on SfM have been carried out. Woodget et al. (2015) used the simple refraction correction method to correct the water depth of a clear and shallow river. However, this method is more suitable for shallow waters less than 2 m deep, which limits its application range. Dietrich (2017) further applied SfM technology to extracting shallow stream bathymetry from multi-view oblique photographs. Later on, Agraflitis et al. (2020) introduced machine learning into correcting image refraction for bathymetric mapping. The two endeavors made the refraction correction method suitable for much deeper water depths.

Spectrally based approaches are built upon either physical or empirical techniques. In the past two decades, many studies based on empirical techniques have been conducted to retrieve water depth by using passive optical remote sensing (Stumpf et al., 2003; Legleiter et al., 2004; Niroumand-Jadidi et al., 2020). Stumpf et al. (2003) developed a ratio transform algorithm to determine the bathymetry of the ocean. The algorithm is capable of retrieving depths greater than 25 m in clear water coastal environments (Jagalingam et al., 2015). Legleiter et al. (2009) mapped river bathymetry based on hyperspectral image data and proposed a depth retrieval algorithm, namely optimal band ratio analysis (OBRA). With the maturity of the aerial platform, the depth inversion based on publicly available aerial images is applied to mapping the bathymetry of rivers (Legleiter, 2013). Recently, digital orthophoto maps (DOM) orthorectified and mosaicked from UAV-acquired overlapping images has gradually replaced traditional aerial images (Colomina and Molina, 2014). Usually, the DOM only records the digital number (DN) values of red, green, and blue bands with a red-green-blue (RGB) camera. When such images are used to estimate the water depth, the model in (DNr/DNg, DNr/DNb) based on the OBRA algorithm is the most widely adopted inversion model (Jaevnicky et al., 2014; Kim et al., 2019).

Currently, UAV-based optical remote sensing has been widely used for mapping the topo-bathymetry of coasts (Brodie et al., 2019; Tsukada et al., 2020), coral reefs (Casella et al., 2016; Storlazzi et al., 2016), rivers (Woodget et al., 2015; Shintani and Fonstad, 2017; Kasvi et al., 2019), reservoirs (Templin et al., 2017; Langhammer et al., 2018; Erena et al., 2019), and aquatic habitats (Tamminga et al., 2015; Kalacská et al., 2018). However, no studies of UAV-based topo-bathymetry of tufa lakes have been performed until now (Profe et al., 2016). The aquatic ecosystem of tufa lakes is very fragile and UAV-based remote sensing technology provides a cost-effective solution for non-contact measurement of topo-bathymetry. Furthermore, with relatively small areas and high transparency, tufa lakes are very suitable for UAV-based optical bathymetry.

In this paper, we applied UAV-acquired RGB imagery and two topo-bathymetry methods, namely refraction correction and water color inversion, to obtain a digital elevation model (DEM) of a transparent tufa lake. In Section 2, the study area and the UAV-acquired data are briefly introduced. Then, the methods are described in detail in Section 3, including UAV data processing, SfM and light refraction correction, and spectral analysis and water color inversion. The resulting DEMs from the two methods are presented and their qualities are assessed in Section 4. The general applicability of the two methods and the factors affecting the DEM quality are discussed in Section 5. In Section 6, we present conclusions of our study regarding the feasibility of UAV-based topo-bathymetry mapping in transparent tufa lakes.

2. Study area and data

2.1. Study area

As shown in Fig. 1, the study area is located in Jiuzhaigou National Nature Reserve, Sichuan, China. This area belongs to the transition zone from Qinghai Tibet Plateau to Sichuan Basin, with the altitude ranging from 2000 m to 2650 m. It has a subtropical to temperate monsoon climate with annual precipitation of 522.9 mm and annual mean air temperature of 7.8 °C. Jiuzhai Valley is world-famous for karst landforms including alpine tufa lakes and waterfalls with abundant calcified deposits. The lake water is generally clear and transparent with various degrees of blue-green color due to absorption and Rayleigh scattering (Li et al., 2020).

In the long-term process of karstification, a large number of tufa lakes have been formed in Jiuzhaigou. As seen in Fig. 1c, there are a group of tufa lakes distributed in Shuzheng Valley, one of the major sub valleys of Jiuzhaigou. From northeast to southwest sequentially lie Double-Dragon Lake, Spark Lake, and Lying Dragon Lake. As shown in Fig. 2a, the shape of Spark Lake was roughly a triangle with a side length of about 150 m. The lake water was transparent and light blue, and abundant tufa deposits could be seen at the lake bottom. However, the destruction of these valuable natural features by geological disasters (e.g., earthquakes) is irreversible. The natural bank on the downstream side of Spark Lake collapsed in the magnitude 7.0 Jiuzhaigou Earthquake, which occurred on August 8, 2017 (Lei et al., 2017). As a result, the water of Spark Lake nearly drained out and the lake basin with opalescent tufa deposits was exposed, making it a natural test site to carry out this study on topo-bathymetry of tufa lakes and validate our results. The original landform of Spark Lake was slightly damaged by localized landslip in some areas, and a small amount of water accumulated in the low-lying areas of the lake bottom. Additionally, the reconstruction of the bank also changed the original nearshore topography (see Fig. 2b).

2.2. UAV image acquisition

Two UAV flights were separately carried out to acquire the RGB images covering the study area before and after the earthquake. The main parameters of the two flights are listed in Table 1. The UAVs used for both missions are equipped with global positioning system (GPS) and inertial measurement unit (IMU), thus synchronously recording the 3D coordinates and the roll, pitch, and yaw angles of the UAV when each image is being taken.

The UAV images of Spark Lake before the earthquake were captured on the late morning of December 9, 2016. The weather was sunny and windless. The flight was carried out with a fixed-wing UAV, which was equipped with a SONY digital camera ILCE-5100. The sensor dimension of the camera is 23.333 mm × 15.556 mm. The focal length of the sensor is 20 mm, and the pixel resolution of RGB images is 4000 × 6000. In the flight route planning, the relative flying height was set as 500 m, the absolute altitude is 2800 m, the along-track overlap was 80%, and the side overlap was 70%. As a result, a total of 72 photos were taken, and covered the entire study area including Spark Lake. The ground sampling distance (GSD) of the images was 10 cm.

The post-earthquake images of Spark Lake were taken at noon on October 10, 2018. The flight was conducted using a DJI Phantom 4 Pro Quadcopter, which was equipped with a digital camera FC6310. The
sensor dimension is 12.833 mm × 8.556 mm. The focal length of the sensor is 10 mm, and the pixel resolution of RGB images is 5472 × 3648. In route planning, we adopted the same flight trajectory as that of the pre-earthquake flight. But the relative flying height was set as 150 m and the corresponding GSD became 5 cm.

3. Methods

In this study, we used UAV-acquired RGB images and applied two topography processing methods to produce DEMs of a transparent tufa lake. First, we captured the RGB images of Spark Lake before and after the Jiuzhaigou Earthquake with a fixed-wing UAV and a drone, respectively, and produced DSMs and DOMs with SfM photogrammetry. As there are no trees or buildings in the test site, the DSMs could be conveniently used as the DEMs. The water depth of Spark Lake was first obtained via refraction correction based on the DEM and the water surface elevation (WSE) before the earthquake. Then, the underwater topography was acquired from the RGB orthophoto using water color inversion. The general applicability of the two methods was fully examined and the qualities of the two resulting DEMs were assessed based on

![Study area](image1.png)

**Fig. 1.** Study area. (a) Location of the study area in Sichuan, China, marked by the star. (b) Jiuzhaigou National Nature Reserve. (c) The distribution of tufa lakes in study area.

![Spark Lake](image2.png)

**Fig. 2.** Spark Lake. (a) Before the earthquake. Black box indicates the selection shown in Fig. 7. (b) After the earthquake. The outlined extents represent the areas where the lake bed has been ruined, flooded, or modified. The geographic coordinate system is WGS 84/UTM zone 48N.
the exposed topography of Spark Lake, which nearly drained after the earthquake. The flowchart for topo-bathymetric mapping of the tufa lake is shown in Fig. 3, which includes photogrammetric approach and spectral depth approach.

Before discussing the details of our methods, several special aspects of tufa lakes must be described. Firstly, compared with large lakes, rivers, and oceans, tufa lakes have smaller surface waves and no obvious water surface flow. In other words, the water surface can safely be assumed planar. Secondly, there are almost no fish, algae, plankton, or suspended matter in the lakes, so the transparency of the lakes is very high. Moreover, there are few impurities on the lake bed. The color of the lakes generally presents a gradient of blue-green. Finally, the water in Spark Lake nearly drained after the earthquake and the basin was slightly damaged. These unique characteristics make our study different from general bathymetry mapping.

3.1. Data processing

3.1.1. DOM and DSM generation

In this study, the UAV-acquired RGB images were processed by Pix4Dmapper, which implements auto aerial triangulation and other functionalities. The camera parameters including position and orientation are first estimated by SFM technology (refer to Section 3.2.1 for more details), and then sparse tie points are extracted from overlapping images by textural matching. After point cloud densification, and image orthorectification and mosaicking, we produced DSMs and DOMs of Spark Lake before and after the earthquake. Spatial resolutions were 10 cm before the earthquake and 5 cm after the earthquake. The raster DSMs were generated by Inverse Distance Weighting (Li and Heap, 2011) after noise filtering and surface smoothing. Finally, both the DOM and the DSM were exported in a tagged image file format (TIFF).

3.1.2. Geographical registration and resampling

The accurate registration of UAV data before and after the earthquake is critical for point sampling and quality assessment of the resulting DEMs. The DOM and DSM of Spark Lake after the earthquake were used as the reference data, and the corresponding data before the earthquake were registered to them. As shown in Fig. 4, a set of ground control points (GCPs) were selected from neighboring zones of Spark Lake including the road and bank, which were of minimum deformation after the earthquake. With these tie GCPs, the horizontal registration was done in ArcGIS, thus the DOMs and DEMs before the earthquake had the same spatial coordinate system as the data after the earthquake. Then we resampled the pre-earthquake DOM and DSM using a Nearest Neighbor algorithm (Tan et al., 2015) to upscale their spatial resolution to match that of the post-earthquake data, namely 5 cm. Likewise, we co-registered the pre-earthquake elevation to the post-earthquake one using the average elevation difference between tie GCPs on the road and bank of the two DSMs.

3.1.3. Bathymetric extent and point sampling

In the pre-earthquake DOM and DSM of Spark Lake, we extracted the elevation of the “water-edge” points along the gentle part of the lake boundary as the WSE (Bandini et al., 2020). The resulting WSE of 2226.93 m was used to delineate the actual topo-bathymetric extent (see Fig. 4) in the pre-earthquake DSM by extracting the area where the elevation was less than the WSE. Then, the bathymetric extent was used as a mask to extract the exact data from pre-earthquake DEM and DOM, and post-earthquake DEM of Spark Lake. In the pre- and post-earthquake DEMs, the minimum elevations of the lake basin were 2214.09 m and 2211.91 m, respectively.

The sample points were critical for establishing a water depth inversion model and evaluating the two resulting DEMs. As shown in Fig. 4, we sampled 900 points in the bathymetric extent of Spark Lake, excluding the areas where the lake bed was ruined, flooded or modified. The

| Table 1 The UAV data acquisition. UAV = unmanned aerial vehicle; GSD = ground sampling distance. |
|-------------------------------|-------------------------------|
| Date             | Platform     | Sensor         | GSD      |
| Pre-earthquake | 2016-12-9  | Fixed-wing UAV | SONY ILCE-5100 | 10 cm  |
| Post-earthquake | 2018-10-10 | DJI Phantom 4 Pro | DJI FC6310 | 5 cm  |

Fig. 3. Flowchart for topo-bathymetric mapping of the tufa lake. (a) Photogrammetric approach, and (b) spectral depth approach.
sample points were evenly distributed as a whole, but more points were collected in shallow areas with relatively large amounts of relief. Their attributes including DN values of RGB bands and elevations were extracted from the spatially aligned pre-earthquake DOM and post-earthquake DEM of Spark Lake, respectively. Among the 900 sample points, 600 training points were used for model establishment, and 300 check points were used for DEM quality assessment.

3.2. Photogrammetric approach

3.2.1. Structure-from-Motion

SfM is a photogrammetric technique that deals with sets of unordered and heterogeneous images for estimating 3D models without prior knowledge of the camera parameters (Westoby et al., 2012). In geosciences, the production of high-resolution DEMs is one of the main applications of SfM photogrammetry (Eltner et al., 2016). When the UAV loaded with a camera passed over the tufa lake, successive overlapping images were captured (Fig. 5). Through feature detection, the keypoints with distinctive contrast or texture in sequential images were automatically extracted and matched. SfM estimated camera parameters of each image, and generated a sparse point cloud based on these keypoint matches (Iglhaut et al., 2019). Then, the point cloud was densified using the multi-view stereo (MVS) algorithm, and the DEM of the tufa lake was finally produced.

In the above process, the camera recorded the received light intensity in images, while the SfM only calculated and generated the DEM according to the textures of overlapping images. The camera and SfM cannot distinguish the lake bed covered with transparent water from
the ground. Therefore, the DEM of the tufa lake produced by SFM was inevitably affected by the light refraction occurring at the water surface, and the actual underwater topography can only be achieved through proper refraction correction.

3.2.2. Refraction correction

According to the refraction law, the propagation direction of light will change at the interface between a relatively dense medium and a relatively sparse medium. Each medium has its own refractive index, which is the ratio of the speed of light propagation in a vacuum to that in the medium. Generally speaking, the higher the refractive index of the material, the stronger the ability to refract the incident light. When light enters water from air, it will refract at the interface of air and water. Similarly, when the camera receives the reflected light from the underwater topography, the reflected light will also refract at the water surface (Mandiburger, 2019).

Due to the existence of light refraction, the obtained water depth will be biased (Westaway et al., 2001). As shown in Fig. 5, the light reflected at the point P enters the camera after being refracted at the water surface. But under normal circumstances, a camera perceives external objects by their reflected light, which obeys the straight-line propagation rule. So we will mistakenly take the perceived ray of light from the actual point P as the reflected light from the initial point P₀. As a result, the original topographic elevation point is uplifted due to light refraction, namely $h_0 < h$. According to Fig. 5, Snell’s Law of light refraction can be expressed as the following equation:

$$\frac{\sin \alpha}{\sin \beta} = \frac{h}{h_0} = \frac{n_1}{n_2}$$

where $n_1$ is the refraction index of water, and $n_2$ is the refraction index of air; $\alpha$ is the incident angle, and $\beta$ is the refracting angle; $h_0$ is the initial water depth before correction, and $h$ represents the corrected water depth.

As the difference (0.13%) between light propagation speed in the air and that in a vacuum is negligible, the refractive index of air is approximately 1.0. Thus the actual water depth can be expressed as the product of initial water depth and the refraction index of water:

$$h = h_0 \times n_1$$

Generally, the refractive index of water in nature is slightly bigger than that of pure water. Multiple studies have demonstrated that the corrected water depth will meet the most requirements if the refraction index of natural water 1.34 is adopted (Westaway et al., 2001; Tamminga et al., 2015; Woodget et al., 2015). In our study, we also used this value as the refraction index of water in tufa lakes for refraction correction.

The specific procedures of refraction correction have been implemented in geographic information system (GIS) environment. First of all, we produced the water depth map of the lake, namely a digital depth model. For a tufa lake, the digital depth model before correction is obtained by subtracting the initial DEM from the WSE. Then, the corrected digital depth model was achieved by the simple water depth correction model with Eq. (2). Finally, we obtained corrected DEM of the tufa lake by subtracting the corrected digital depth model from the lake WSE using Eq. (3). Here, the WSE was used as the intermediate value for the conversion between the absolute elevation of the underwater terrain and the water depth.

$$E = WSE - h$$

where $E$ represents corrected elevation of the underwater topography.

3.3. Spectral depth approach

3.3.1. Band ratio models

OBRA is an empirical technique that infers fluvial bathymetry by identifying the band combination that yields the best regression model between log band ratio values and water depth (Legleiter et al., 2009). It can be considered as a standard approach for implementation of the Stumpf ratio model (Niroumand-Jadidi et al., 2020). OBRA is not only suitable for multi/hyper-spectral images, but also widely used for RGB images, including UAV-based RGB imagery. Previous studies have demonstrated that the natural logarithm of the ratio between the green and red bands, namely ln(DNg/DNr), can be used to retrieve the water depth of shallow, clear rivers (Shintani and Fonsstad, 2017; Kim et al., 2019).

Generally, spectrally based approaches must consider the entire radiative transfer process. The total radiance received by the sensor includes contributions from the bottom, water column, water surface, and atmosphere, but only the bottom-reflected radiance contains bathymetric information (Niroumand-Jadidi et al., 2020). Factors such as atmospheric effects, water surface reflections, and scattering within the water column will introduce uncertainty to the bathymetric estimation. Regardless, band ratio models (Stumpf’s model and OBRA) have been demonstrated to be relatively robust and can be used to retrieve bathymetry in coastal/inland waters (Stumpf et al., 2003; Legleiter et al., 2009).

3.3.2. Water color inversion

When propagating through a water body, electromagnetic waves will be reflected, scattered, and absorbed (see Fig. 6). The color of lake water depends on the selective absorption and scattering of light. In general, pure water has less absorption of blue light, so it appears blue. In addition, molecular scattering may occur in some particularly transparent waters. According to Rayleigh scattering, the shorter the wavelength, the stronger the scattering, which is another reason why the water seems blue.

For extremely transparent water bodies like tufa lakes, the water has generally an extraordinary high transparency due to the tufa’s strong fixation effect on suspended materials. As the short-wave light is strongly scattered by CaCO₃ and other particles, the lake water usually seems to exhibit a range of blue-green colors (Li et al., 2020). As seen in Fig. 6, with the water depth increasing, the color observed by human eyes gradually changes from blue-green to dark blue. Therefore, we can infer the water depth of a tufa lake according to its water color distribution as recorded in RGB images by a consumer-grade camera.

Band ratio models are usually considered to be the first choice for water depth inversion in coastal areas and shallow rivers, but they cannot well inverse the water depth of tufa lakes. ln(DNg/DNr) can do shallow bathymetry because of the exponential attenuation of red band with water depth increasing (Legleiter, 2013) as illustrated in Fig. 8a. However, it has a poor performance in transparent deep water. As shown in Fig. 7a, there is a tufa barrier lying under the water of average depth more than 12 m. The red band image (Fig. 7b) has nearly no information about the underwater topography, which is consistent with Fig. 8a in the water of depth more than 10 m. On the contrary, the green and blue bands (Fig. 7c, d) are sensitive to the change of water depth and contain more bathymetric information. In addition, a tufa lake usually shows a blue color with higher transparency compared with the shallow sea. The color of a tufa lake is more affected by Rayleigh scattering (Li et al., 2020). It is possibly the reason why Stumpf’s model, which is suitable for coastal areas, does not work well for a tufa lake. In addition, the high-altitude environment where the tufa lakes are located has a thin atmosphere, and atmospheric effects have little influence on the water depth inversion.

As illustrated in Fig. 8b, c, the green band has an approximately linear relationship with water depth, while the blue band changes little as water depth increases. These observations reflect the principle that a shorter-wavelength band is sensitive to bottom types, while a longer-wavelength band is more responsive to changes in depth (Legleiter et al., 2009). As a result, the difference between two bands will potentially eliminate some systematic errors and uncertainties. Therefore,
we proposed a band difference model based on blue and green bands to estimate the water depth of tufa lakes:

\[ h = a \times (DN_B - DN_G) + b \]  

(4)

where \( h \) represents estimated water depth, \( DN_B \) and \( DN_G \) are the DN values of blue band and green band, respectively, and \( a, b \) are empirical coefficients.

The relationships between band combinations of red, green, and blue bands and water depth are presented as scatter plots, as shown in Fig. 8d, e, and f. In order to compare the water depth inversion potentialities from different band combinations, including \( \ln(DN_G/DN_R) \), \( \ln(DN_B)/\ln(DN_C) \), and \( DN_B - DN_G \), we executed the linear regression analysis between the calculated values of the above models based on the pre-earthquake orthophoto and the corresponding post-earthquake relative depth values, respectively. According to Fig. 8d, the coefficient of determination \( R^2 \) of \( \ln(DN_G/DN_R) \) is 0.71, and this model exhibits a good performance in shallow water. But with the water depth increasing, its performance decreases rapidly. As seen in Fig. 8e, with the \( R^2 \) of 0.75, Stumpf’s model does not perform as well here as in coastal areas. As shown in Fig. 8f, the model \( DN_B - DN_G \) we proposed achieves the best performance among the above models with the highest \( R^2 \) of 0.85. In addition, our model also demonstrates a good fit across a range of water depths. Therefore, water color inversion based on the band difference \( DN_B - DN_G \) is selected as the bathymetric inversion model for the transparent tufa lake in our study. Finally, we obtained the inversed DEM of the tufa lake by subtracting the water depth calculated with Eq. (4) from the WSE.

4. Results

4.1. Resulting DEMs

The resulting DEMs from refraction correction and water color inversion were presented in Fig. 9a, b, respectively. In Fig. 9a, the corrected DEM of Spark Lake was obtained based on the initial DEM with Eqs. (2) and (3). As shown in Fig. 8f, the coefficients \( a, b \) in
Eq. (4) were determined as 0.1839 and 4.341 by linear regression analysis with training points. Thus, the inversed DEM of Spark Lake (Fig. 9b) was achieved based on the pre-earthquake DOM using Eqs. (4) and (3). In the corrected and inversed DEMs, the minimum elevations of the lake basin were 2209.72 m and 2212.84 m, respectively.

The elevation values of the resulting DEM by refraction correction generally decreased relative to the initial DEM generated by SfM photogrammetry. The deeper the water depth was, the more obviously the elevation decreased. As a result, the maximum water depth of Spark Lake changed from 13 m to 17 m after refraction correction. In comparison

Fig. 8. The relationship between bands or band combinations and water depth. (a) red, (b) green, (c) blue, (d) ln(DN_b/DN_r), (e) ln(DN_b)/ln(DN_r), and (f) DN_b-DN_r.

Fig. 9. DEMs and DoDs. (a) DEM of refraction correction, (b) DEM of water color inversion, (c) DoD between corrected and post-earthquake elevations, and (d) DoD between inversed and post-earthquake elevations. DoD = DEM of difference.
with the initial DEM, there were still some abnormal bulges at the lake bed shown in the red dotted box (Fig. 9a), but these bulges did not exist in Fig. 9b. This comparison implied that the abnormal bulge was induced by SM photogrammetry.

As for water color inversion, the resulting DEM also showed the actual underwater topography of Spark Lake, and the maximum water depth was about 14 m. Comparing DEM in Fig. 9a with that in Fig. 9b, the latter shows more details than the former at the same spatial resolution, but the latter was more disturbed by such factors as impurities and shadows. In Fig. 9b, there were some sporadic abnormal depressions shown in the black dotted box. As a whole, the elevation transition is relatively gentle in Fig. 9a, while the elevation transition is relatively distinct in Fig. 9b.

4.2. DEM quality assessment

In order to validate the resulting DEMs of the two methods, a total of 300 check points in the exposed basin of Spark Lake were collected (shown in Fig. 4). Comparing the elevation values from the two resulting DEMs with those of the check points, we produced the DEM quality assessment results in Fig. 10a, b.

As seen in Fig. 10, the $R^2$ and root mean square error (RMSE) were 0.88 and 1.32 m for refraction correction, and 0.86 and 1.37 m for water color inversion, respectively. As a whole, the DEMs produced by the two methods had similar quality. In shallow areas, both methods slightly overestimated water depth. In water depth from 2 m to 12 m, the corrected elevation had a relatively small error compared with the reference elevation. However, with the further increase of water depth, the corrected elevation was not consistent with the actual underwater topography of the lake. The inflection point occurred at the depth of 12 m (Fig. 10a). As for water color inversion, the estimated elevation had good consistency with the reference elevation when the depth was greater than 3 m. There was no obvious inflection point in the water depth range (Fig. 10b), so we could infer that the performance of water color inversion would be less affected by deep water in tufa lakes. Nevertheless, the turbidity and transparency of the lake water would still impose a maximum detectable depth at some point.

The DEM quality was also influenced by the impurities and shadows at the lake bed for water color inversion. Generally, the opalescent tufa deposits provided a relatively impurity-free background. There were two types of shadows in tufa lakes. One was the large shadow cast by the nearby trees or mountains, and the other was the slight shadow caused by the subtle underwater relief of the tufa lakes. The latter was the reason for the sporadic abnormal depressions shown in the black dotted box of Fig. 9b.

In order to further analyze the DEM errors, we computed the DEMs of difference (DoD) by subtracting the two resulting DEMs from that obtained by SM photogrammetry after the earthquake. The elevation error sizes and the spatial distributions were displayed in Fig. 9c, d for refraction correction and water color inversion, respectively. The two DoDs indicated similar systematic elevation errors as a whole, mainly in the ruined areas and construction areas. The underestimated elevation errors around the bulging areas in Fig. 9d were significantly bigger than those in Fig. 9c. It was principally caused by the slight shadows occurred around the terrain relief. Furthermore, the elevations of refraction correction were seriously underestimated in deep water area, compared with those of water color inversion. In Fig. 9c, a notable patch of overestimated elevation errors appeared at the corresponding position of the red dotted box in Fig. 9a.

5. Discussion

5.1. Factors affecting DEM quality

In our study, multiple factors could have affected the DEM quality. Although Spark Lake is only 5 km away from the epicenter (Lei et al., 2017), the overall topography of the study area has not been directly changed by the Jiuzhaigou Earthquake. Spark Lake was actually the only lake indirectly influenced by the bank collapsing. Although excluding the areas where the lake bed has been ruined, flooded or modified, the precision of training points and check points is inevitably influenced to some extent. In addition, errors and uncertainties were probably introduced in the process of acquisition and processing of UAV images. Firstly, the spatial resolutions of the UAV images taken in the two separate UAV flights are different. Secondly, the DSMs and DOMs before and after the earthquake cannot be accurately matched in the process of geographical registration due to a lack of measured GCPs (Martínez-Carricondo et al., 2018). Especially when registering the elevation, one of the major error sources was our use of the average elevation difference of tie points in the two DSMs. Finally, the WSE, as the intermediate value for the conversion between the water depth and the DEMs, was critical for accurate estimation of underwater topography (Woodget et al., 2019). Therefore, the qualities of the resulting DEMs were actually the cumulative result of all the errors and uncertainties mentioned above.

5.2. Method comparison

The two methods of refraction correction and water color inversion retrieve the underwater topography of tufa lakes from photogrammetric approach and spectral depth approach, respectively. The former corrects the underwater topography using the principles of geometrical
optics, whereas the latter is based on the spectral characteristics of tufa lakes. The two methods can be compared in terms of applicable waters, detectable depth, and performance stability. As for applicable waters, refraction correction is usually applied to clear and shallow waters, while water color inversion is more suitable for tufa lakes with transparent blue-green. In terms of detectable depth, refraction correction is more suitable for water depths not exceeding 2 m (Dietrich, 2017). But for tufa lakes with high transparency, the effective water depth can be substantially increased up to 12 m in our study. Unlike refraction correction, water color inversion is less restricted by water depth, but affected by water transparency due to the inherent limitations of passive optical depth retrieval (Legleiter and Fosness, 2019). As for performance stability, refraction correction is less influenced by environmental change than water color inversion. Generally, different environmental conditions could lead to differences in water color and the refractive index of water. Even the same tufa lakes will show different colors under various conditions, such as seasonal variation, solar elevation angle, and meteorological conditions. Thus, the water color is influenced by more factors than the refractive index.

In most cases, the two methods can largely retrieve the underwater topography of tufa lakes, but errors could occur for certain reasons. For refraction correction, elevation anomalies occurred in deep water or areas of the basin with a uniform texture. In the process of SM photogrammetry, due to the lack of tie points among overlapping images, the resulting point cloud based on through-water dense image matching is sparse or even missing in the water area with poor bottom texture (Mandlburger, 2019). The keypoints matching depends on the presence of distinctive textures among overlapping images. Generally, refraction correction is to stretch the initial DEM obtained by point interpolation and densification. Therefore, refraction correction cannot eliminate the elevation anomalies caused by the point cloud missing. For water color inversion, shadow areas will be created in the water due to light blockage by trees or mountains, or the fluctuation of underwater terrain. In this case, the water area can be divided into shadow region and non-shadow region, and the water depth can be separately estimated (Shintani and Fonstad, 2017). However, the shadows that occur in tufa lakes are usually scattered and difficult to distinguish.

5.3. Deficiencies and potential improvements

In our study, two methods of applying UAV-acquired RGB images to mapping the topo-bathymetry of a transparent tufa lake were presented and compared. However, there were still some deficiencies. On the one hand, both the photogrammetric approach and spectral depth approach belong to passive optical remote sensing. Active remote sensing technologies such as LiDAR and sonar are not used, though their limitations were described in Section 1. On the other hand, the two methods presented are not suitable for topo-bathymetric mapping of tufa lakes on all occasions. As for a lake with high turbidity, passive optical remote sensing might not detect the bottom of the lake basin if it exceeds the sensor’s maximum detectable depth. Additionally, in refraction correction, it is not considered that the refractive indexes have a slight discrepancy in different water bodies. In water color inversion, the blue and green bands of standard RGB cameras have a low spectral resolution, which could limit their ability to infer the topo-bathymetry.

For the above deficiencies, improvements are expected to be made in future studies. First of all, the refractive index of a specific tufa lake needs to be accurately measured before being applied to refraction correction. Secondly, the water depth inversion based on UAV-borne hyperspectral remote sensing (Legleiter and Harrison, 2019) needs to be further studied for tufa lakes. Finally, the integration of various remote sensing technologies will possibly meet the requirements of topo-bathymetric mapping under different conditions (Williams et al., 2014; Bandini et al., 2018).

6. Conclusions

In this study, we attempted to carry out topo-bathymetric mapping of a transparent tufa lake using UAV-acquired RGB imagery. The principal conclusions we reached are as follows:

- The approaches of topo-bathymetric mapping with refraction correction and water color inversion using UAV-acquired RGB imagery in transparent tufa lakes are feasible and effective.
- Refraction correction demonstrated a good performance within 12 m water depth of the transparent tufa lake, which far exceeded its normal effective depth in other shallow water bodies.
- The difference between blue and green bands (\(D_{\text{NIR}}\)) was determined as the optimal band combination for water color inversion, and it nearly exhibited a fine performance across the entire range of water depth.
- The DEM produced by water color inversion was depressed by slight shadow, while the abnormal bulge of the DEM produced by refraction correction was inherited from the initial DEM generated by SfM photogrammetry.

Although our study provides two effective topo-bathymetric methods for transparent tufa lakes using UAV remotely sensed data, they are possibly restricted by water turbidity, maximum depth, and illumination conditions. Therefore, it is still a very challenging task to accurately measure the underwater terrain of tufa lakes without disturbance. On some occasions, active remote sensing and even field-based surveying are still needed in turbid and deep waters. In future research, it is not only necessary to further optimize the models, but also more important to integrate different bathymetric technologies and improve the cooperative ability of active and passive remote sensing.

Declaration of competing interest

The authors declare no conflict of interest.

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