

A PRACTICAL METHOD FOR CALCULATING LAKE VOLUME OVER TIME:
Using GPS to measure water availability in small lakes inhabited by the mountain yellow-legged
frog (*Rana muscosa*) in Kings Canyon National Park, California

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ABSTRACT

To determine changes in water availability for the imperiled mountain yellow-legged frog (MYLF, *Rana muscosa*), we used resource-grade GPS and ArcGIS with 3D Analyst to estimate lake volume, water surface area and perimeter as lake levels decreased during the summer. Water availability is crucial to MYLF because tadpoles require multiple years before metamorphosing into adults, and breeding is now often restricted to small, shallow fishless lakes that sometimes dry during the summer. To track intra- and inter-annual changes in volume we developed a method that did not require permanent depth markers or survey-grade GPS equipment to collect highly accurate altitude data. We constructed 3D lake bottom topography (bathymetry) in 3D Analyst of lakes at the beginning of summer (maximum water volume) by systematically recording horizontal GPS points on the lake bottom while simultaneously measuring the water depth at each point with a tape measure. Lake perimeters were mapped with GPS multiple times as the lakes receded during the summer, and their water surface areas (SA) were calculated. Because each surface area value is presumed to occur at a unique lake depth, we determined the volume for each perimeter mapped by adjusting the “height of plane” in 3D Analyst until the reported “2D area” matched our calculated water surface area (SA). The difference in volume estimated for one lake using this method and the volume calculated using a depth marker ranged from 0% to 12%. This technique is a practical method for measuring volume changes in small lakes where permanent markers can not be established.

INTRODUCTION

The mountain yellow-legged frog (MYLF; *Rana muscosa*) is endemic to the Sierra Nevada mountains of California (USA), and, although it was common and widely distributed in the past, its range has declined by >80% in the last 90 years (USFWS 2003). In the Sierran range, MYLF’s primary habitat includes high elevation lakes and slow-moving portions of streams (1370 – 3660 meters elevation; Zweifel 1955). Although the lakes were historically fishless, hybrid trout (*Onchorhynchus* spp.) have been intentionally introduced into larger lakes, where they prey on the native amphibians. The strong detrimental effects of predatory trout on MYLF are well documented (Bradford 1989; Drost and Fellers 1996; Knapp and Matthews 2000), and it is likely that the presence of fish in a lake severely limits that lake as a breeding

habitat for MYLF.

Consequently, most frog breeding in our study area is observed in smaller (fishless) lakes, some of which occasionally dry up during the summer. High elevation MYLF tadpoles need two to four years of permanent water to complete their larval development (Zweifel 1955; Bradford et al. 1994; Knapp and Matthews 2000), thus the restriction of breeding to ephemeral lakes could result in



Figure 1: Lake #5 in September 2002. Typical (fishless) MYLF habitat; notice the drawdown during summer (2002) – blue line indicates the lake shore in late June.

population decline and local extinction due to repeated tadpole mortality caused by summer lake drying. It is also likely that the lake drawdown (see Figure 1) during the summer, without complete drying, impacts the MYLF population, and potentially reduces breeding success.

The overall goal of the Dusy Basin Lake Mapping study is (1) to quantify changes in water volume, surface area and shoreline length in selected small lakes in Dusy Basin; and (2) to determine whether these changes in lake parameters relate to changes in population levels of different life stages of the MYLF, and its breeding success. These objectives required the development of a novel method for tracking volume changes because the protected status of the study site precluded installation of permanent survey markers. The method also had to overcome the limitation of most resource-grade GPS equipment that does not collect accurate vertical-point (altitude) data needed for generating bathymetry of shallow lakes.

In this paper we present the development of a method to track year-to-year volume changes in small lakes where permanent survey markers can not be installed, using resource-grade GPS equipment and ArcGIS 3D Analyst.

STUDY SITE

The study was carried out in the upper Dusy Basin (37°5'40" N, 118°33'45" W; elevation 3460 m), located in the Sierra Nevada Mountains within the Kings Canyon National Park, California, USA. The Basin is part of designated wilderness, and is adjacent to a popular hiking trail. The limited soil substrate (decomposed granite with a thin soil layer) and harsh winter climate result in alpine vegetation of herbs, low shrubs, and whitebark pine (*Pinus albicaulis*).

The study area comprises a cluster of 15 glacial lakes and six small streams (Figure 2). Most lakes are small, shallow (< 1 ha, < 2m depth), clear and oligotrophic. Some lakes dry up during the summer, and all freeze over during the winter (with some freezing through to the bottom). Lake fauna includes aquatic invertebrates, two species of frogs (MYLF, and Pacific treefrog *Hyla regilla*), and one species of aquatic snake which preys on the frogs (the declining Mountain garter snake, *Thamnophys elegans elegans*; Matthews et al. 2002). All Dusy lakes were historically fishless, but hybrid trout (*Onchorhynchus* spp.) were intentionally introduced into larger lakes in the Sierra Nevada (Knapp 1996). Today the largest, deepest Dusy lake (Lake 1), and water bodies downstream of it, support a breeding trout population.

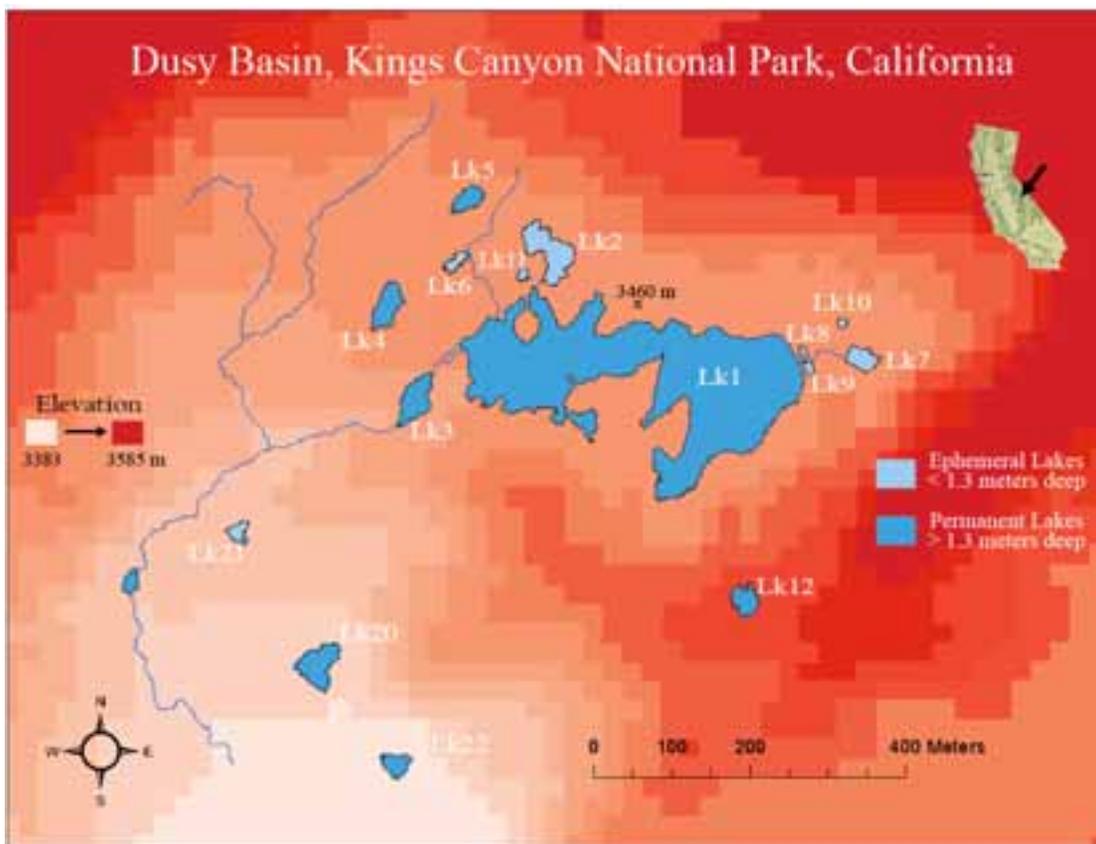


Figure 2: Study area lakes in Dusy Basin, Kings Canyon National Park, California.

METHODS

Overview

To determine water surface area, water volume, and shoreline length, we used global positioning system (GPS) to map the bathymetry (underwater topography) of each lake, and to map the lake perimeter as water levels receded throughout the summer months.

GPS Equipment and settings

We used a Trimble ProXRS GPS receiver (Trimble Corporation, Sunnyvale, CA) with real-time satellite-based differential correction (Omnistar Inc, Houston, TX). After field-testing the receiver in 2002, we estimate the horizontal accuracy in Dusy Basin at better than 30 cm. The high-elevation, treeless environment in Dusy Basin provides a clear “view” of the sky – a key condition for good GPS reception – and because of this, we were able to set our GPS receiver parameters to maximize data quality, as recommended by the manufacturer: high “horizon” angle (15°), large number of required satellites (“overdetermined 3D” mode), low levels of acceptable HDOP/PDOP errors (4/6), real-time correction required for each data point, and point averaging using ≥ 3 data points. Vertical GPS position information (altitude) was not used because the vertical accuracy of the ProXRS – like vertical position accuracy of all resource-grade GPS receivers – is considerably less (up to 1 m error) than the horizontal accuracy, and using vertical position data would result in unacceptable error in bathymetry surface. Therefore we measured lake depth (see next section) to generate bathymetry.

Mapping lakes for bathymetry and initial water volume

In order to create bathymetry and determine initial water volume, we mapped the underwater topography of each lake bottom at the beginning of the 2002 field season (early July 2002), when the lakes were filled to their high water marks. To create a bathymetry surface we waded through each lake, systematically recording horizontal GPS points on the lake bottom while simultaneously measuring the water depth at each point. To measure water depth we used a measuring tape attached to a survey rod (accurate to about 1 cm), except in the central part of Lake 1, which is much deeper than the other lakes (≈ 9 m vs. 0.2 – 2.3 m), where we used a weighted line dropped from a float tube to determine depth (accurate to approximately 0.5 m). We focused the data collection at the water’s edge, the (underwater) slope breaks, centers of

large underwater flats, stream inlets and outlets, and other areas where the bathymetry was changing. Where the bathymetry was uniform (i.e. flat or gently sloping), we recorded one point approximately every 0.75 m.

Modeling bathymetry: relative depth method

Mapping the bathymetry in each lake resulted in an irregular grid of points, which we used to create a three dimensional bathymetric surface in ArcView 8.1 / ArcGIS 3D Analyst (ESRI Corp., Redlands, CA) using the triangular irregular network (TIN) procedure (Figure 4). We used the measured depth of each point (i.e. -0.40m) – and NOT the GPS-reported altitude – for the elevation information which is required to create the TIN surface (the “height source” in ArcGIS terms). Consequently, the depth of each lake is a relative depth based on the water surface in early July 2002. This “relative depth” approach has been used before in mapping lakes (e.g. Hartnett, 2002), with the advantage that it eliminates the problem of relying on the GPS elevation data to create bathymetry.

We also recorded around the shoreline of each lake a set of points which we had estimated to be about 20 cm above the water line. In the 3D TIN surface model these points form a “rim” around each lake – which would otherwise be formed by the initial water line – thus reducing the errors in water volume that result if the “edge triangles” created by the TIN procedure contain water.

Tracking changes in water surface area and shoreline length

To determine the changes in water surface area and the shoreline length (circumference of water surface), we returned to each lake 4 times during the 2002 field season to map the edge of the receding water surface. Each water surface was treated as a polygon in ArcGIS, and area and circumference (i.e. shoreline length) were calculated. Islands and emergent rocks were subtracted from the final water surface area.

Tracking volume changes #1: The standard reference depth approach

At the beginning of bathymetry mapping in 2002, we marked a deep spot on the bottom of each lake – the “reference point” – with a survey stake and measured the depth there (“reference depth”) to use in “height of plane” calculation (below). The survey stakes were only used for the duration of the summer as we were not allowed to establish permanent markers in

any of the lakes. The depth of the reference point was re-measured concurrently with each shoreline mapping (above), and provided one means to calculate water volume. To calculate volume, we used each lake’s 3D TIN bathymetry model and ArcGIS – 3D Analyst. To determine the “height of plane” for use in 3D Analyst we took the [initial water depth at the reference point] minus the [current depth at the reference point]. Thus, for the initial volume calculation, the “height of plane” was zero, and for subsequent volumes the “height of plane” was a negative number (i.e. - 0.4 m, as all depth measurements were negative).

Tracking volume changes # 2: The surface area matching (SA) approach

The “relative depth” method of bathymetry modeling has a disadvantage in that – unless the initial water surface or the bathymetry surface is referenced to a permanent survey marker (which can not be installed in our study area) – it becomes impossible to relate the water depth measured during one year to the depth measured in subsequent years. This is because the subsequent year’s depth values would need to be back-calculated based on the *initial water level of the first year at the same point*, and that level and point are now unknown. While it would be theoretically possible to re-locate the first-year’s reference point on the lake bottom using its GPS coordinates, the underwater topography of the lakes is so uneven that a small error in the

(horizontal) location of the reference point will likely result in a comparatively large error in the back-calculated depth values. We therefore employed a method that relied on hypsometry (a depth – surface area relationship), i.e. the concept that for each water depth there will be a unique surface area (SA) value (Fig. 3a). Thus, if we know the water

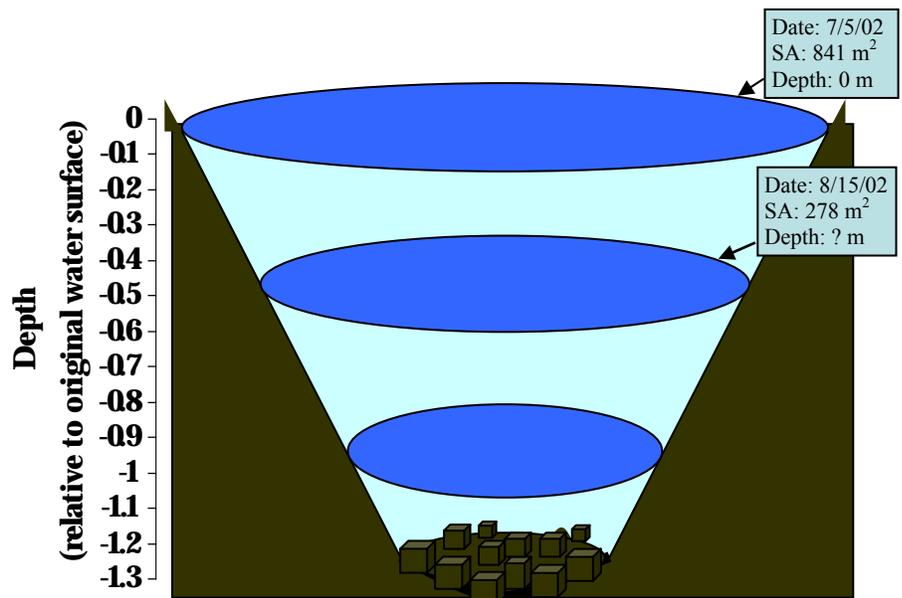


Figure 3a: Schematic section view of a lake with water surface at different dates. See Fig 3b for further explanation of the surface area-matching method of computing lake volume.

surface area, we can find the height at which the water surface lies, which is the “height of plane” (#1 in Fig. 3b) in 3D Analyst. To measure water volume this way we calculated the area of the water surface (SA) at each re-mapping of the lake, then iteratively adjusted the “height of plane” in 3D-Analyst until the reported 2D area (#2 in Fig. 3b) equaled the area of our water surface. The corresponding volume (#3, Fig. 3b) calculated by 3D Analyst (“below plane”, #4 in Fig. 3b) was then taken to represent the actual water volume.

Note that the reported Surface area in the 3D Analyst *Area and Volume Statistics* box is the surface area of the lake bottom (which takes into account the surface roughness and topography), and is NOT the water surface area that we are trying to match. The correct “matching” surface area is the “2D area” (#2 in Fig. 3b). Also note that we used a Z factor to convert our centimeter depth measurements into meters to match the horizontal units; this is not necessary if the horizontal and vertical measurement units are the same.

We validated the SA-matching method by comparing the results with those obtained by the reference depth method in four lakes in 2002. We present complete data for one perennial lake, Lake #5, and abbreviated data for the other lakes in the following section.

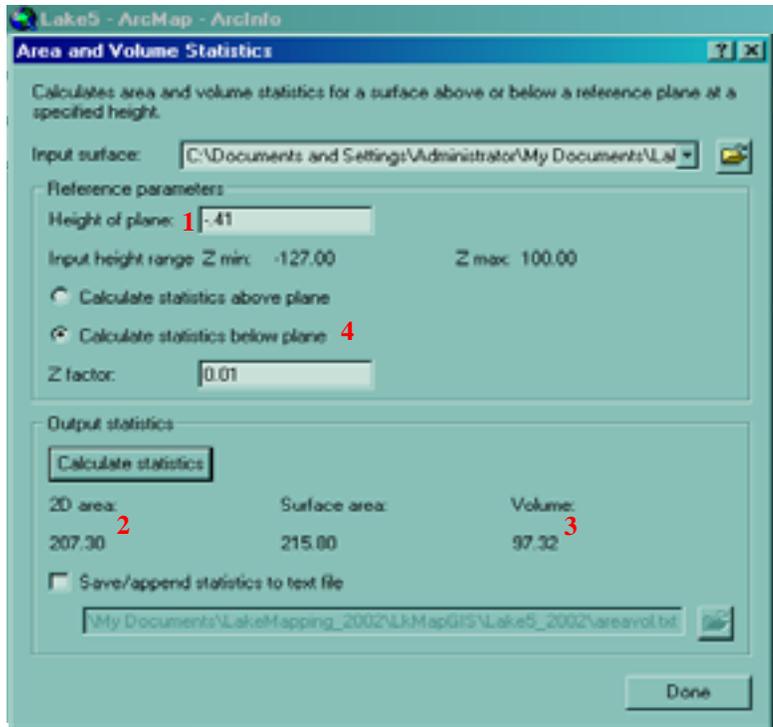


Figure 3b: Mechanics of the Surface area matching method of volume calculation in ArcGIS 3D Analyst. Our objective is to compute the lake volume on 8/15/2002 after mapping the water surface. The height of plane required for calculation (#1 in red) is unknown, but the 2D area (#2) – i.e. the water surface area – is known. Thus, we iteratively adjust the height of plane until the reported 2D area equals the known water surface area, and then read the calculated volume (#3).

RESULTS

We mapped all 15 Dusy Basin lakes using GPS, and built bathymetry surfaces using the measured depth at each GPS point. We present here data for Lake #5, which serves as one of the breeding lakes for MYLF (see Figure 2 for location). We collected a dense grid of GPS points with measured depth, and used it to create a 3D bathymetry model using the TIN procedure (Figure 4).

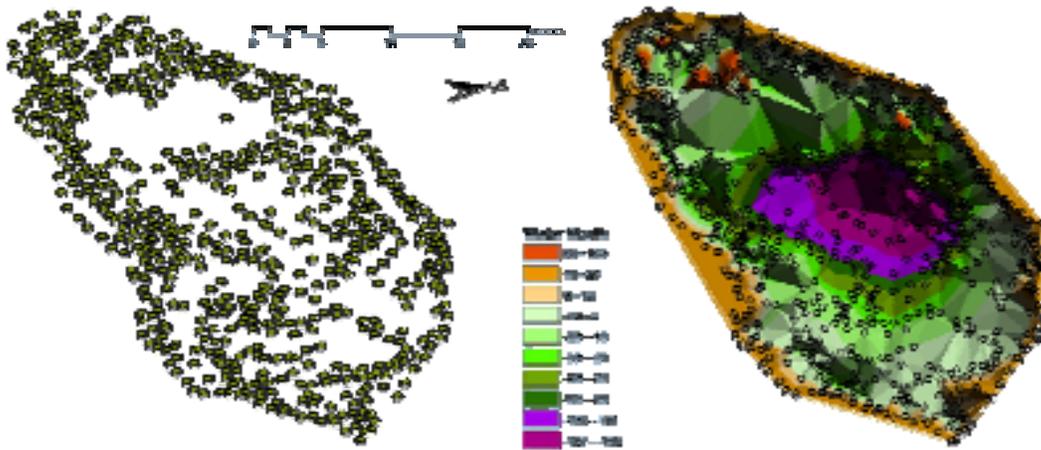


Figure 4: Bathymetry mapping (Lake 5). Plan view of GPS points (left) and TIN surface built using the water depth measured at each of those points (right). Water depth is in *centimeters*, based on the water level at the time of mapping. The lake has a max depth of 127 cm. Notice a relatively dense grid of GPS points (for such a small lake).

Table 1 shows the water volume of Lake 5 as it receded during the summer of 2002, calculated using the standard reference depth approach (V_{Std}) and our SA- matching approach (V_{SA}). The “Difference” values reported in Tables 1 and 2 and discussed later refer to the discrepancy in the lake volume values reported by the two approaches, and are calculated as difference between the two volumes (i.e. $[V_{SA} - V_{Std}]$) divided by the average of the two volumes (i.e. $0.5*[V_{Std} + V_{SA}]$).

Fig 5 Volume change in Lake #5 (Summer 2002); oblique view. Blue area: current water surface; blue lines indicate previous water surface extent; depth legend as in Fig. 4

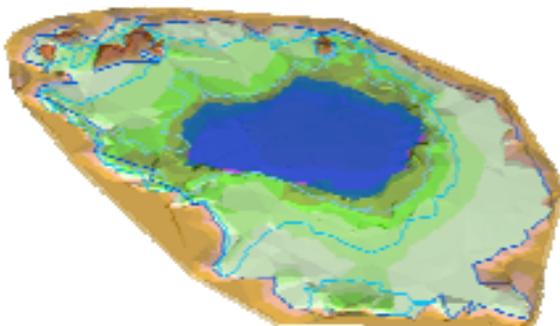
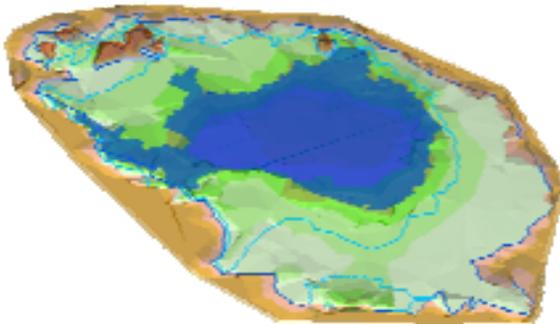
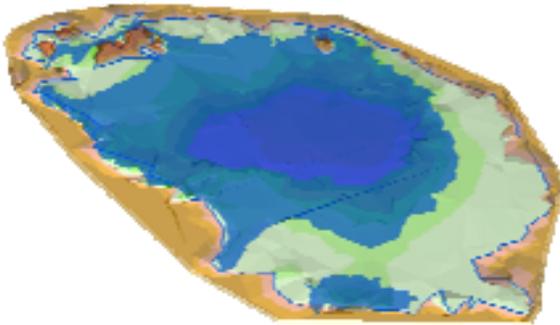
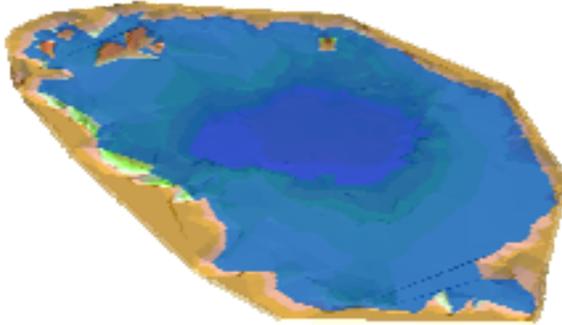


Table 1: Comparison of two volume calculation methods for Lake 5.

Date	Volume #1- Standard method	Volume #2- SA-matching method	Difference $\frac{V_{SA}-V_{Std}}{(V_{Std}+V_{SA})/2}$
7/05/02	276.65 m ³	276.66 m ³	0 %
7/28/02	204 m ³	188 m ³	- 8 %
8/15/02	141 m ³	125 m ³	- 12 %
9/22/02	83 m ³	75 m ³	- 10 %

The SA-matching method was validated using data from 3 other lakes as well (Lakes 2, 4, and 6 – Table 2). Lake 2 and 6 are shallow ephemeral lakes, with Lake 6 drying most years. Lake 2 is the most important lake for breeding in the basin, but it dries completely in drier years. Lake 4 is a permanent and relatively deep lake. We have continued re-mapping the Dusky lakes, and data from 2002, 2003 and 2005, as well as bathymetry surfaces for all the lakes are available upon request.

Table 2: Comparison of the two volume calculation methods for Lakes 2, 4 and 6.

Lake	Date	Ref. Depth (cm)	Volume (m ³) #1- Standard method	Volume (m ³) #2- SA-matching method	Difference $\frac{V_{SA}-V_{Std}}{(V_{Std}+V_{SA})/2}$
2	7/4/02	68	700.3	658.6	-6.2%
	7/28/02	No ref. depth recorded		437.4	
	8/15/02	15	35.98	46.68	25.9%
	8/25/02	Lake was dry	0	0	
4	7/5/02	230	1082.5	1077.6	-0.5%
	7/29/02	218	900.8	933.4	3.6%
	8/15/02	204	714.0	796.9	11%
	9/4/02	190	559.3	617.3	9.9%
	9/22/02	176	438.2	485.5	10.2%
6	7/5/02	43	57.95	55.94	3.5%
	7/28/02	18	0.92	9.49	164.7%
	8/15/02	Lake was dry	0	0	

DISCUSSION

We used this surface-area matching method in 2002, 2003 and 2005 (using 2002 bathymetry) and found it to be a useful and accurate approach for tracking volume changes in small lakes through a single season and over multiple years. The difference in volume estimated using this method and the volume calculated using a depth marker at the beginning of the summer when lakes are fuller is less than 7%. We have validated the surface area matching method at the beginning of summer (when the effects of lake bottom microtopography on volume calculation are the least) to show that when the two methods should produce similar volumes, they do. It was also necessary for us to use the surface area matching method in the National Park wilderness area where permanent survey markers could not be installed. This method can be implemented with a standard ArcGIS package that includes 3D Analyst extension. The only additional steps required for this analysis are “cutting out” the emergent rocks and islands from the water surface polygon and then calculating water surface area. Surface area can easily be calculated in the attribute table with a short script in ArcGIS.

The method does have several prerequisites and limitations. In general, the calculation of small volumes depends heavily on an accurate bathymetry surface. To generate such a surface it requires collecting many closely-spaced points in smaller lakes or in lakes with uneven underwater topography. Furthermore, because the water depth *as measured during the GPS-points collection* is used to generate the bathymetry surface, the points must be collected in one or two days so that there is no change in water surface elevation during GPS data collection; this may prove challenging for larger lakes. Also, there is a choice of surface-building methods. We chose the simplest method for our study (TIN), although “smoothly” interpolated (e.g. kriged) surfaces might be more appropriate in other cases.

In very shallow lakes (those mostly < 50 cm) with complex and uneven bottom microtopography (crevices, boulders, mud etc.) this method is likely to produce rather different results from those obtained by relying on a reference-depth approach. For example, in the shallow Lake 6, the difference in calculated volume between the two methods increased dramatically as the lake receded during the summer: from 3.5 % difference at the beginning of summer, to over 165% difference (9.5 m^3 vs. 0.9 m^3) when

the lake was nearly dry. Thus – even though in the above case our estimates (avg. depth x water area) show that the SA-matching method gave the correct result – we caution that the accuracy of *any* volume estimation method in such shallow lakes is likely to be compromised by the ability of the user to accurately measure the depths and model the bathymetry surface. In our case, this ability was constrained both by the accuracy of our GPS equipment, and by the complex microtopography of the lake bottom (e.g. the many boulders in Lake 6 and large waterlogged-mud areas in Lake 2).

The SA-matching method is inappropriate for volume calculation in one type of water body – those with mostly vertical slopes – where a declining water level results in a volume change, but water surface area remains nearly constant (e.g. water storage tanks). This is an additional problem in Lake 2, where the depth can decrease by as much as $\frac{1}{4}$ without much change to the water surface area. Here, measuring the easily found maximum depth is probably the best method of estimating volume.

In most wilderness lakes, the SA-matching method is likely to produce good volume estimates when used with the resource-grade GPS equipment capable of collecting high-accuracy horizontal position data, and the lower accuracy of vertical position data collected by such equipment is unimportant, because the altitude information is not used. In addition, the SA-matching method avoids the installation of permanent survey markers which might be objectionable in some areas. Ultimately, a lake's characteristics should determine which volume estimation method should be used.

Our results will help to determine if there is a link between water availability and frog breeding success. If a strong correlation exists, then habitat management plans for MYLF should ensure breeding access to larger, deeper lakes that are not prone to summer drawdown.

ACKNOWLEDGEMENTS

We thank Dr. David Graber, Sequoia-Kings Canyon National Park Science Advisor, and the many field assistants who have helped with the study.

Trade names and commercial enterprises are mentioned solely for information. No endorsement by the USDA Forest Service is implied.

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