*Estimating Depth of Small Mountain Lakes by Photo Measurement Techniques**

KARL E. MOESSNER,
Forester, Intermountain Forest and Range Expt. Sta., Forest Service, U. S. Dept. of Agriculture, Ogden, Utah

ABSTRACT: *Current emphasis on recreation has created a need for land managers to know the extent and utility of the lake resource in high mountain areas. Photogrammetric measurements of lake area, perimeter, length, and breadth are utilized in many recreational inventories, but the possibility of estimating lake depth offers a new challenge to our profession. Techniques developed for estimating depth in shallow ocean areas have proved impractical in lake inventory because of varying clearness and bottom types.*

A new technique based on photogrammetric measurement of shore slopes is usable on medium scale resource photography. Photo estimates of the shallow area on the 21 lakes so measured were not significantly different from those made from field soundings at 10 times the cost.

INTRODUCTION

THE current emphasis on outdoor recreation has created acute need for knowing more about the lake resource of the Mountain West. Recreational planners and resource managers visualizing possible fishing or boating use, would like to know approximate depths as well as number and size of the high mountain lakes. Although these lakes are small, they are numerous and often virtually inaccessible, and ground surveys to obtain even these meager data may be costly and time consuming. Photogrammetry offers about the only low cost, yet reliable, method of obtaining complete counts and surface measurements of this widespread water resource. The possibility that lake depths might also be estimated from aerial photos prompted the research reported in this paper.

KARL E. MOESSNER

THE PROBLEM

The literature of the past 15 years contains only a few discussions of photogrammetric techniques used in estimating the depth of shallow water. These techniques, which have been used primarily on ocean beaches, are of two types. One, reported by Moore,[1] Theurer,[2] and others relies on a series of photos taken with various films and filters. Each film and filter combination records a

[1] Moore, J. Grange. "The Determination of the Depths and Extinction Coefficients of Shallow Water by Air Photography Using Color Filters," pp. 163, 217–21, *Royal Soc. of London, Series A*, No. 816, Vol. 240, Mathematical and Physical Sciences. 1947.

[2] Theurer, Charles. "Color and Infrared Experimental Photography for Coastal Mapping," pp. 565–69, PHOTOGRAMMETRIC ENGINEERING, Vol. XXV(4), illus. 1959.

* Presented at March 24–30, 1963 ASP-ACSM Convention, Hotel Shoreham, Washington, D C.

different light penetration, and on each the point at which bottom details become visible can be used as a datum and mapped as an underwater form line. Field soundings are used to determine the average depth of these various planes, and a final contour map is prepared. This technique is sharpened by the use of infrared, panchromatic, and color film, and multiple cameras taking all photos simultaneously.

The other method, described and used by the armed services during World War II, is a direct measurement technique using large-scale, low-altitude photos taken when a slight breeze ruffles the water surfaces and makes them visible. It is then possible to measure parallax differences between the surface and underwater details, adjust this measurement by light refraction tables, and obtain a measurement of depth.

McCurdy[3] and others have stressed the difficulty of determining from aerial photos the approximate depth of underwater features even in clear ocean water. Their studies indicate that accuracy of these measurements depends upon scale and quality of the aerial photos as well as bottom type and water conditions. These known techniques offer small hope in solving the problem of depth measurements in high mountain lakes. The reasons are several:

1. Both water clearness and bottom materials vary. If photo interpreters depend on differences in photographic tone to indicate different water depths, consistent estimates of depth are almost impossible where light penetration varies between lakes. In this study the lakes ranged from high cirque lakes, with turbid reddish-colored water, photographing opaque on panchromatic film, to relatively clear moraine lakes where bottom details photograph in 8 to 12 feet of water (Figure 1).

Tonal differences are related to the light reflectance quality of the lake bottom as well as water clearness and depth. Some of these lakes have light-colored sand or marl bottom near shore, but others have dark rocks. Some have black peat bottoms. In many lakes all these conditions are encountered together with extensive areas of underwater vegetation (Figure 2). A change from light to dark photographic tone usually indicates an increase in water depth, but in these lakes such a change may indicate merely a change from light to dark bottom materials.

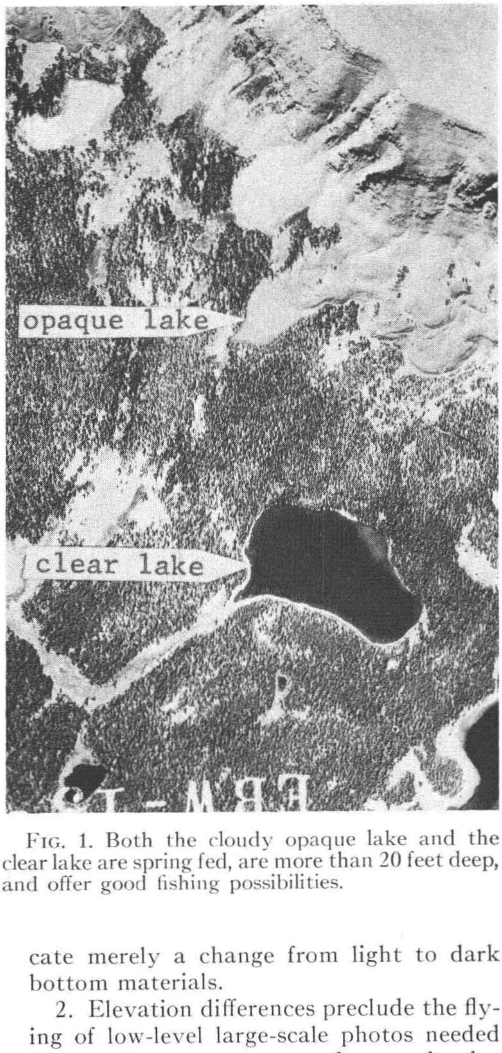

FIG. 1. Both the cloudy opaque lake and the clear lake are spring fed, are more than 20 feet deep, and offer good fishing possibilities.

2. Elevation differences preclude the flying of low-level large-scale photos needed for parallax measurement of water depths. Cirque lakes and many of the moraine type are located at high elevations close to precipitous 1,000- to 2,000-foot mountain slopes (Figure 3).

3. The necessity for using existing resource photography. Since these lakes are scattered over extensive areas now covered by medium-scale resource photography, land managers prefer techniques usable on these photos. Any method requiring new multiple photos taken with various films and filters would probably be considered too costly.

The problem then is: Can existing resource photography be used to estimate depth in small mountain lakes with varying water clearness and bottom type?

The data used in this paper were obtained

[3] McCurdy, P. G. "Coastal Delineation from Aerial Photographs," pp. 550–55, PHOTOGRAMMETRIC ENGINEERING, Vol. XVI(4). 1950.

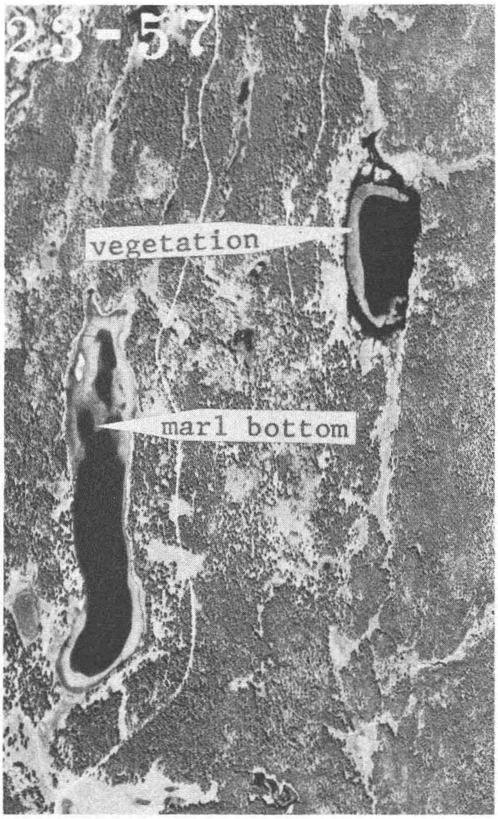

FIG. 2. Emergent vegetation and marl bottom appear much the same on panchromatic photos of these typical lakes.

as part of an extensive study of the recreational relationship of the water resource of the north slope of Utah's Uinta Mountains. This study is now being made by personnel of the Intermountain Forest and Range Experiment Station, U. S. Forest Service, in cooperation with Utah State University, and the Intermountain Region (R-4) of the U. S. Forest Service. The lake and stream inventory in the Uinta Mountains, made as part of this recreational study, offered an excellent opportunity to investigate the possibilities of photo measurement techniques in estimating the depth of high mountain lakes.

Preliminary Studies

The variability of these lakes as well as the limitations of the available aerial photos seemed to indicate that a new approach would be needed. Tonal differences and visible underwater details might aid the interpreter in estimating depths on some clear lakes, but even here the results would surely be erratic unless checked by some type of photo measurement. The known methods of depth estimation were clearly impossible on the many opaque lakes.

Limited field observations showed that many shore slopes continued almost unchanged for a considerable distance under water (Figure 4). This indicated that lake depths should be predictable from photo measurements of shore slopes. This theory was tested by means of 65 slope lines distributed on several of the more accessible lakes. These lines were first laid out approximately at right angles to the lake shores. The shore slopes were then measured on the 1:20,000-scale aerial photos by parallax methods. Field crews measured the shore slope with Abney level and also made depth soundings 100 feet from shore at the marked locations. These data were analyzed.

Average photo and field measurements and their standard errors, as well as correlation coefficients, are shown in the following tabulation:

Mean bank slope measured on photos (per cent)	17.2±1.9
Mean bank slope measured on the ground (per cent)	18.1±2.0
Mean lake depth at 100 feet from shore (feet)	12.4±1.4
Correlation coefficient photo to field slopes	.931**
Correlation coefficient photo slope to field depth	.874**

** Significant at 99-per cent level.

Shore slopes measured on aerial photos were not significantly different from those measured on the ground, although both were significantly greater than lake depths measured 100 feet from shore.

These measurements were also stratified by slope per cent class. Mean slope per cent measured on photos and mean depth obtained

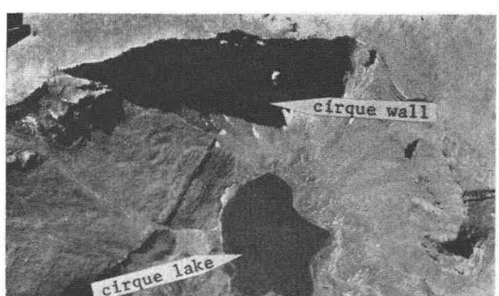

FIG. 3. This cirque lake, at nearly 11,000 feet elevation, lies at the base of a 1,000-foot cirque wall. This common location precludes use of continuous strip large scale photography used in beach studies.

by field soundings are compared in the following tabulation:

Photo slope class (per cent)	Samples	Photo		Field	
		Mean slope	$\sigma_{\bar{x}}$	Mean depth	$\sigma_{\bar{x}}$
	N				
1.0– 3.9	10	2.8	±0.2	3.5	±0.4
4.0– 6.9	6	5.2	±0.4	4.5	±0.8
7.0– 9.9	11	8.7	±0.2	6.2	±0.3
10.0–14.9	13	11.7	±0.4	8.6	±0.8
15.0–19.9	6	16.9	±0.7	13.9	±1.9
20.0–29.9	9	24.1	±1.2	18.7	±2.2
30.0–49.9	6	39.5	±2.0	29.8	±4.5
50.0+	4	64.0	±5.6	35.8	±8.0

Note: $\sigma_{\bar{x}}$ Standard error of the mean.

This preliminary research showed that bank slopes and lake depths were related and also that photo measurements of bank slopes were about as useful as those made on the ground. These findings might be used to predict maximum lake depth or lake area within specific depth limits.

The use of shore slopes in predicting lake depths is based on the assumption that the shore slope can be projected unchanged under water. This is probably true for a limited distance, but eventually this line becomes a curve because of sedimentation in the lake basin (Figure 5). The error in plotting a specific underwater contour by shore slope becomes less as the shore slope increases. Conversely, if the shore slope remains constant, the error of location increases as the depth increases.

This suggests the use of a regression to obtain true depths from measured slopes. This approach was not pursued since many more field soundings would have been required to compare actual and predicted depth at varying distances from the lakeshore, and since the results at best would simply be a refinement of an untested technique.

Lake area has more meaning to resource managers than maximum lake depth. Surface areas would also be the simplest figures to use in evaluating methods of locating specific depth contours. For these reasons, this study was laid out to test the usefulness of bank slope measurements in estimating surface area overlaying water 0 to 15 feet deep. The 15-foot depth was used because it seemed to be a median depth for many high mountain lakes, and is thought useful in segregating the areas of biological importance during the summer season. The same measurement

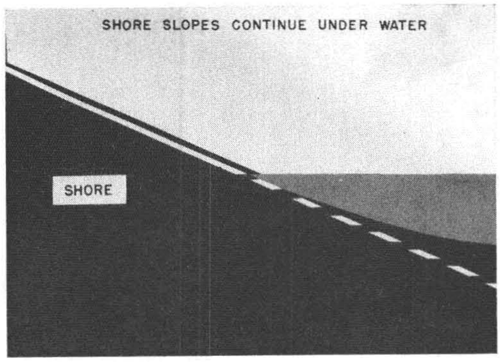

FIG. 4.

techniques, if proved reliable, could be used with refinements in predicting other selected depths of importance to fishing or boating use.

Results of the preliminary study indicated feasible leads to the principal objectives of the study as listed below.

OBJECTIVES

This study develops and compares photo methods for using shore slopes to predict depth in small mountain lakes. It attempts to answer these questions:

1. What photo interpretation methods can be used to estimate the area of water less than 15 feet deep in a lake or group of lakes?
2. How do these estimates compare with those made from field soundings?
3. Does relative accuracy vary by method, interpreter, or the physical characteristics of the lake?
4. How do costs of photo estimates compare with those of estimates from field soundings?

THE STUDY

The basic data for this study were obtained from measuring 21 lakes located between 9,500 and 11,500 feet elevation along the north slope of Utah's Uinta Mountains. These lakes were considered a fairly typical sample of the more than 1,200 small lakes and ponds tallied and classified on aerial photos. All were of glacial cirque or moraine origin, and ranged from 2 to 65 acres in area with maximum depths of from 12 to 70 feet. Bank slopes ranged from 2 to 70 per cent; very few lakes had an average bank slope of more than 30 or less than 10 per cent. Bottom materials varied from talus through boulder, gravel, sand, to muck or peat, with all types occuring

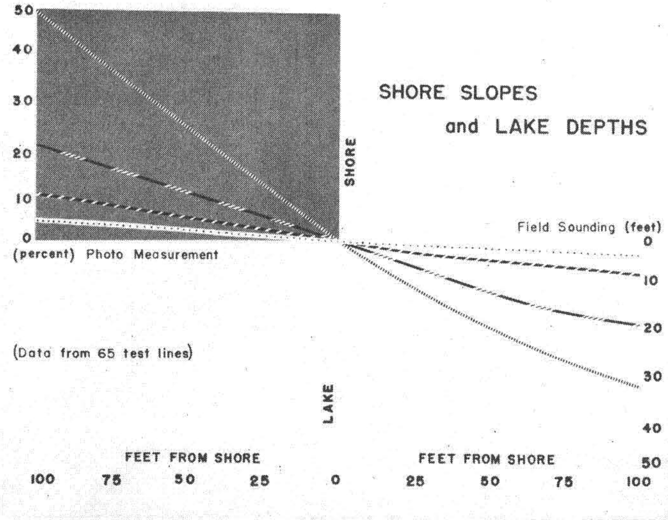

FIG. 5. Comparison of shore slopes measured on photos with lake depth measured by sounding at 100 feet from shore.

on some lakes. The depth at which bottom details became visible ranged from less than 2 feet in the opaque lakes to more than 15 feet in those classified as clear. Underwater vegetation was for the most part sparse but noticeably present in a few lakes.

Independent photo estimates of the area less than 15 feet deep were made for each lake by each of five trained interpreters (Figure 6). These estimates were analyzed by comparing them with a like estimate prepared from field soundings. The mean areas for groups of lakes and the standard errors of estimate were both used in the evaluation.

TYPE OF AERIAL PHOTOS

The aerial photos used in this study were U. S. Department of Agriculture nominal 1:20,000-scale panchromatic photos taken with $8\frac{1}{4}$-inch focal-length camera. Larger scale photography taken with different film and filters might result in better data, but a primary objective of this study was to develop techniques usable on resource photographs available in the files of most land managing agencies.

In order to produce a usable photo map of the selected underwater contour, some enlargement of the contact prints was necessary. Those portions of the prints giving stereo coverage for each of the selected lakes were copied at 2:1 scale. Six sets of identical contact prints were made from the enlarged negatives. Each interpreter received a set of the 1:10,000-scale prints on which to plot his interpretation of the 15-foot contour. The sixth set was used to prepare a plot of the contour based on field soundings. Although the enlarged photos were used for interpretation, slope measurements were all made on the 9- by 9-inch 1:20,000-scale prints.

PHOTO MEASUREMENTS AND INTERPRETATIONS

All photo measurements were made by using simple photo interpretation aids and lens stereoscopes. Elevation differences used in computing slope per cent were measured by parallax wedge; horizontal distances by 0.001-foot rule. Three photo methods of estimating shallow area were tested:

1. Graphic method based on photo measurement of shore slopes.
2. Formula method also based on measurements.
3. Graphic method without slope measurement.

These methods seemed to cover the range of possibilities, both for precision and practical use of the existing resource photography.

1. GRAPHIC PHOTO METHOD USING SLOPE MEASUREMENTS

Working independently on the 1:20,000-scale contact prints, each of three interpreters selected and measured an average of 10 slope lines for each sample lake. Each interpreter then computed and plotted on the stereo-blowup the distance from shore to the 15-foot depth contour (Figure 7). While viewing this blowup stereoscopically, the interpreter sketched a line connecting the 15-foot depth points, taking full advantage of any underwater beaches or other bottom features visible on the blowup. Although the interpreters were limited to 10 slope lines, these were not equally spaced around the lake perimeter. Instead, each interpreter located his lines independently on slopes he considered significant. Interpreters were guided by the preliminary studies, which had indicated that one or two slope lines should be measured on the flat slopes usually associated with inlet and outlet, and that the others could be distributed over the steeper slopes. On these small glacial lakes the flat slopes apparently resulted from valley fill and had some controlling effect on depth of the lake basin.

Although interpreters used identical scale, flying height, parallax, and conversion factors previously computed for each lake, their interpretations were considered independent since each measured his own slope lines, and each prepared his own plot of the 15-foot depth contour on an unmarked stereo enlargement.

This is considered the most advanced of the three methods in terms of use of measurement techniques and interpretive judgment. In it, the interpreter uses his photogrammetric skill in measuring and projecting shore slopes. He also uses interpretive skill in selecting the slope lines and in extending the depth contour between projected points by referring to bottom details and shore topography.

2. FORMULA METHOD

Included because of its simplicity and possible use on extensive surveys, the formula method assumes the lake to be circular and lying in a bowl-shaped basin (Figure 8).

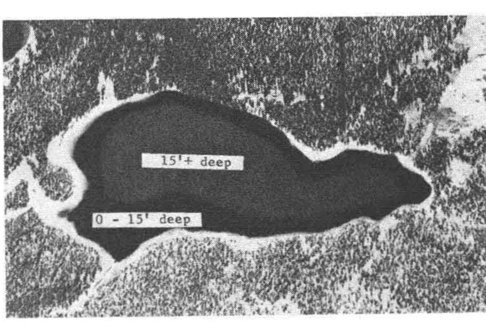

FIG. 6. Photo interpreters estimated surface area of water less than 15 feet deep on each of the 21 lakes.

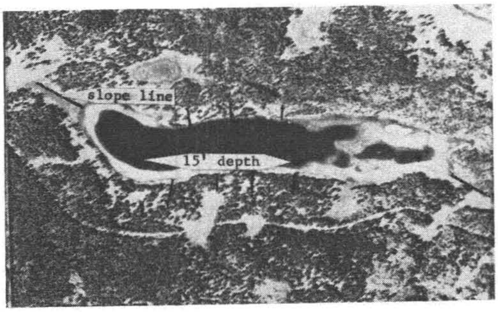

FIG. 7. At each of the 10 measured slope lines the interpreter indicates his projection of the 15-foot depth point. While viewing the photos stereoscopically, he then sketches the underwater contour in reference to visible bottom features and shore detail.

Therefore, the acres in the exterior shallow zone can be computed by the formula:

$$A_{\text{acres}} = \frac{(P_m - \pi\overline{W})\overline{W}}{43{,}560}$$

where

P_m = the measured perimeter of the lake.
$\overline{W}$ = the average width of the shallow zone predicted from shore slopes.

Lake perimeter is easily measured on aerial photos, and average width of the shallow zone can be estimated from a few slope lines. Since the interpreter has little opportunity to vary his estimate by interpretation, the method is largely photogrammetric. Area computations for this method were based on average width obtained from slope measurement made from Method 1.

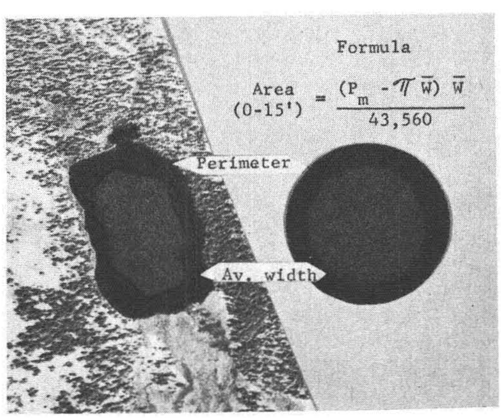

FIG. 8. The area between the two circles, 10.6 acres, was computed by formula from photo measurements of perimeter and shore slopes. It is about 17 per cent greater than the 9.0-acre shallow area mapped between the lakeshore and the 15-foot depth contour plotted from field soundings.

3. GRAPHIC PHOTO METHOD WITHOUT SLOPE MEASUREMENT

Two other interpreters, also working independently, sketched their interpretation of the 15-foot depth contour on additional sets of blowup photos. These interpreters were instructed to use underwater features, shorelines, and their conception of slope, but were not allowed to make any slope measurements on the lakes. Since many photo interpreters consider measurements an unnecessary refinement in their art, this last method was included in order to evaluate any precision gained through photo measurement.

In both graphic methods, subjective interpretation is used in sketching the depth contour in relation to visible underwater details, but the first technique can be considered partly objective in that the contour is located at several points by direct photo measurement of shore slopes.

FIELD MEASUREMENTS AND CONTROL PLOT

Field crews visited each of the 21 sample lakes and made 15-foot depth soundings from portable rubber rafts. Soundings were adjusted for any change in water level since date of photography and were located independently of previously selected photo slope lines. The 15-foot depth locations were selected at reasonable intervals by the man making the soundings. As each point was located, bearings were taken simultaneously with staff compasses from two or more locations on the lakeshore. These bearings were later used in the office to locate the sounding points on a photo map, and these points were used to sketch a completed field interpretation of the 15-foot depth contour, which was accepted as the correct or control plot for the analysis. In the preliminary tests of depth prediction, soundings were located by taping from shore and also by stadia measurements. Neither method proved feasible with portable rubber rafts. Since base points could be located precisely from the photo maps, triangulation was used in preference to the other techniques.

AREA MEASUREMENTS

Except for the formula method all lake areas were determined by dot count using a microdot templet having 1,096 dots per square inch. Dot counts were made while the photos were viewed stereoscopically. Total area and area less than 15 feet deep were counted and then converted to acres by a factor based on the scale of the photos at the lake.

Basic Data, Analysis, and Results

The basic data available for analysis are listed below:

1. The shoreline perimeter and gross area of 21 sample lakes; each lake is classified by size, origin, water clearness, shore cover and material.
2. An estimate of shallow area (0- to 15-foot depth) for each of the 21 lakes obtained by plotting field soundings. This was used as *control for the experiment.*
3. A total of eight aerial photo estimates of shallow area for each lake consisting of:
   a. Three graphic photo estimates based on measured shore slopes.
   b. Three computed photo estimates based on measured shore slopes and lake perimeter.
   c. Two graphic photo estimates made without measurement of slopes.

Below are eight shallow area estimates for a typical small lake with a total area of 4.5 acres.

Photo methods	*Photo estimates*		
	No. 1	*No. 2*	*No. 3*
	Acres		
1. Graphic—slopes measured	3.1	3.1	2.7
2. Formula—slopes measured	3.2	3.3	2.3
3. Graphic—no measurements	1.6	4.3	—

The field estimate for the same lake was 2.8 acres.

4. Estimates of the relative cost of field depth soundings and of each of the three photo techniques.

For analysis, the lakes were first grouped into five size classes used in the original North Slope inventory. Average lake area as well as field and photo estimates of shallow area are shown for each class (Table 1).

Analyses of variance were used to test the estimates of shallow water for each lake class and for the total of all lakes. Significant differences were found at the 5-per cent level in some lake classes, but not in the averages of all 21 lakes. These data were further analyzed by T-tests using all possible combinations of estimates within each lake class. This analysis showed that no photo method resulted in class averages significantly different at the 5-per cent level from the class average obtained by field soundings. The few significant differences were between two photo interpretations made by different methods. Since

TABLE 1

MEAN ESTIMATED SHALLOW AREAS BY LAKE SIZE CLASS AND METHOD OF ESTIMATING

Lake size class	Lakes checked	Gross area	Field estimates based on soundings	Photo estimates					
				Method 1 Graphic—Slopes measured		Method 2 Formula—Slopes measured		Method 3 Graphic—No measurement	
			Shallow area	Estimates	Area $\sigma_{\bar{x}}$	Estimates	Area $\sigma_{\bar{x}}$	Estimates	Area $\sigma_{\bar{x}}$
	N	Acres	Acres	N	Acres	N	Acres	N	Acres
1	3	3.56	2.11 ±0.44	9	2.15 ±0.25	9	2.66 ±0.29	6	2.23 ±0.48
2	6	7.96	6.73 ±0.81	18	6.02 ±0.31	18	7.04 ±0.38	12	5.88 ±1.02
3	3	13.31	10.44 ±1.89	9	9.30 ±0.30	9	11.06 ±0.45	6	9.10 ±1.17
4	5	27.29	15.89 ±2.74	15	14.81 ±1.40	15	19.02 ±1.92	10	18.30 ±2.07
5	4	46.53	19.54 ±2.89	12	23.50 ±1.30	12	24.34 ±1.46	8	34.03 ±4.26
All	21	20.04	11.22 ±1.56	63	11.36 ±1.01	63	13.14 ±1.11	42	14.14 ±1.91

$\sigma_{\bar{x}}$ =Standard error of the mean.

this analysis indicated that the average shallow area for any lake class could be estimated by any of the three photo methods about as well as by field soundings, it helped very little in selecting the method that would work best. Instead the standard error of estimate,[4] a convenient measure of the range and variability in the estimates of individual lakes, was used to evaluate the three methods.

These standard errors of estimate in acres and in per cent of gross lake area were first computed with data sorted by lake size class (Table 2). Next the data were sorted by physical characteristics such as bank slopes, clearness, bottom types, bottom material, and shoreline development.[5] Standard errors of estimate were then computed for each of these classes (Table 3).

Statistical tests showed that for the most part Methods 1 and 2, based on measured shore slopes, resulted in lower standard errors of estimate, which often did not differ significantly. Method 3, with no measurements of shore slopes, usually had higher standard errors of estimate, which often differed significantly from Method 1. These relations between methods remained essentially the same for any stratification tested.

Costs of the various methods were estimated and compared. Precise costs were difficult to obtain since the lakes varied greatly in size and accessibility, and since the techniques used were experimental and to a certain extent evolved as the work progressed. Estimated average costs including aerial photos for a 20-acre mountain lake are shown in the following tabulation:

Field soundings	$52.25
Photo method 1	7.25
Photo method 2	4.50
Photo method 3	5.00

Field costs are very difficult to estimate since the depth soundings would rarely be taken without collecting other field data such as water temperature, chemical composition, and bottom vegetation. Travel time is a large item in total cost of field work. For taking

[4] The standard deviation of the differences between paired field and photo estimates of the shallow area for individual lakes.

[5] A limnological classification based on the percentage relationship of the measured perimeter to the perimeter of a circle having equal area.

TABLE 2

STANDARD ERRORS OF ESTIMATE FOR SHALLOW AREAS BY LAKE SIZE AND METHOD OF ESTIMATING

Size class	Lakes checked	Average		Method 1 Graphic—Slopes measured			Method 2 Formula—Slopes measured			Method 3 Graphic—No measurements		
		Gross area	Field shallow area	Estimates	Sy		Estimates	Sy		Estimates	Sy	
	N	Acres		N	Acres	Per cent	N	Acres	Per cent	N	Acres	Per cent
1	3	3.56	2.11	9	±0.33	± 9	9	±0.84	±24	6	± 0.95	±27
2	6	7.96	6.73	18	±1.40	±18	18	±1.06	±13	12	± 1.60	±20
3	3	13.31	10.44	9	±1.98	±15	9	±2.10	±16	6	± 3.86	±29
4	5	27.29	15.89	15	±2.49	± 9	15	±5.03	±18	10	± 7.15	±26
5	4	46.53	19.54	12	±5.60	±12	12	±8.76	±19	8	±18.49	±40
All	21	20.04	11.22	63	±2.84	±14	63	±4.50	±22	42	± 8.49	±42

Note: Standard error of estimate, *Sy*, is the standard deviation of the differences between field and photo estimates for the individual lakes. Per cents are based on gross areas.

TABLE 3

STANDARD ERRORS OF ESTIMATE BY SELECTED CLASSIFICATIONS AND METHOD OF ESTIMATING

Class	*Lakes checked*	*Average lake area*		*Method 1 Graphic—Slopes measured*			*Method 2 Formula—Slopes measured*			*Method 3 Graphic—No measurements*		
		Gross area	*Shallow area*	*Esti-mates*	*Sy*		*Esti-mates*	*Sy*		*Esti-mates*	*Sy*	
				N	*Acres*	*Per cent*	*N*	*Acres*	*Per cent*	*N*	*Acres*	*Per cent*
Water clearness												
Opaque	6	16.10	8.96	18	±2.58	±16	18	±3.87	±24	12	± 7.30	±45
Clear	15	21.62	12.12	45	±2.96	±14	45	±3.44	±16	30	± 9.11	±42
All	21	20.04	11.22	63	±2.84	±14	63	±4.50	±22	42	± 8.49	±42
Slope Class												
Per cent												
1–14	5	14.85	12.51	15	±2.83	±19	15	±3.50	±24	10	± 2.55	±17
15–25	10	20.44	10.20	30	±3.58	±18	30	±5.40	±26	20	±10.37	±51
26+	6	23.71	11.84	18	±1.46	± 6	18	±3.70	±16	12	± 8.97	±38
Shore Material												
Talus	6	16.37	8.72	18	±1.91	±12	18	±4.05	±25	12	± 7.16	±44
Boulder	10	20.64	10.38	30	±3.47	±17	30	±4.49	±22	20	± 9.70	±47
Sand-Silt	5	23.30	15.89	15	±3.45	±15	15	±5.30	±23	10	± 8.36	±36
Shoreline Development												
Per cent												
100–119	4	6.07	4.67	12	±1.19	±20	12	±0.69	±11	8	± 1.14	±19
120–139	10	22.62	10.77	30	±3.75	±17	30	±5.08	±22	20	±10.62	±47
140–159	3	16.07	11.20	9	±1.02	± 6	9	±1.68	±10	6	± 5.86	±36
160+	4	30.56	18.90	12	±2.46	± 8	12	±5.96	±20	8	± 9.71	±32

soundings, a three-man crew is required; a rubber boat and other field tools must be packed to each lake. In wilderness areas it may be necessary to pack in and establish a base camp. The above tabulation of costs for measuring an average lake includes average travel time from a centrally located base camp to nearby lakes. If costs to establish base camps were included, this estimate might easily be doubled for lakes in wilderness areas.

On the whole, there is little difference in the costs of the three photo methods. Differences are especially insignificant in comparison with the cheapest field estimate, which may easily cost 5 to 10 times as much as the most precise photo method.

The usefulness of the methods described in this paper depends largely on the objectives of the survey to be made. For most work the graphic photo method relying on photo measurements of shore slopes appears to be the most precise and would undoubtedly be the best method for those interested in and equipped to do photo mapping. It would be most valuable on intensive studies of individual lakes, particularly if photo maps were to be the end product, and if photography at the desired scale could be obtained. It would also be more useful on the larger lakes. But when extensive recreational areas containing many small lakes and ponds must be inventoried using existing 1:15,000- or 1:20,000-scale resource photography, graphic techniques have disadvantages. The cost of photo enlargements needed for mapping as well as the increased cost of area measurement can hardly be justified if the objectives are merely to measure and classify a number of lakes for recreational purposes. Under these conditions the second method based on direct photo measurements converted by formula should prove most useful.

CONCLUSIONS

For the type of lake and the area studied, available data indicate:

1. Any one of the three photo methods tested could be used to estimate average shallow area for a group of lakes; such an estimate would not differ significantly from that obtained by limited field soundings.

2. Of the three methods tested, Method 1 (combined photogrammetric and photo interpretation techniques) generally gives the closest estimates of shallow area for individual lakes. Two out of three estimates by this method should not differ from field sounding estimates by more than ±14 per cent of the gross lake area.

3. Estimates of shallow area made by Method 1 vary less between interpreters than estimates based on the other two methods; this relative precision is affected little by lake size, clearness, or average shore slope.

4. Variation in the cost of photo methods has little significance when estimates from field soundings may cost 5 to 10 times as much as the most precise photo method tested.

5. Shore slope measurements for estimating depth and the formula method for estimating shallow area are the most promising leads for further research.