Bausch and Lomb Graduate Award

Surface Water Velocity Measurements on Delavan Lake Using Aerial Photographs

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INTRODUCTION

THE OBJECTIVE of this study was to assist in analyzing possible ways of improving the water quality of Delavan Lake, which has become quite polluted. Good circulation of the lake could solve the pollution problem. First, however, knowledge of existing currents in the lake was needed.

The fundamental concept applied in obtaining the currents of the lake was taking repeated time-lapse aerial photographs of floating targets which were placed on the lake surface before photographing. Photogrammetric solutions produce target positions, and repeated photos thus yield target movements. These movements, divided by the corresponding time lapses, produce velocity vectors.

It is a simple problem to get the positions of targets if they are stationary. This situation was more difficult, however, because (1) the targets were moving and (2) the lake area of interest could not be covered by a single photograph.

DESCRIPTION OF DELAVAN LAKE

Delavan Lake is located in Walworth County in the state of Wisconsin, approximately 75 miles northwest of Chicago. It is 3.6 miles long and 0.6 miles wide. Its surface area is 2.8 square miles, its mean depth is 25 feet, and its maximum depth is 55 feet. The inlet is located at the northeast corner of the lake, and the outlet is located at the northwest corner, as shown in Figure 1. Many resort and recreation facilities lie along the lake's shore line.

DETERMINATION OF PHOTO SCALE

Design of the photography was one of the most important elements of this problem. Factors to be considered in selecting photo scale were (a) area to be covered, (b) size of targets available, and (c) visibility of targets on the resulting photographs for measurement. This latter factor would be affected by reflection of the sun and by ripples of the lake surface.

The size of the lake area of interest was fixed. A large number of targets were made and available from a previous project, and thus the target dimensions were also considered fixed. Two types of targets were available. The first, used to monitor surface currents, were 2-ft by 2-ft square targets made of styrofoam. The second type, used to measure subsurface currents, were 18-inch diameter circular styrofoam targets with drogues submerged approximately 4 ft below the surface (see Figure 2).

Thus, the remaining factor, target visibility, was the critical one to be considered in selecting photo scale. Prior to the actual project, an experimental photographic mission was performed on Lake Wingra in Madison, Wisconsin. Twelve targets of different colors and configurations were placed on the lake. These included all white, all yellow, black circle on white background, black cross on white background, black-and-white stripe, and black numerical figures on white background. Then, a photograph was taken from a flying height of 3600 ft using a 6-inch focal length camera. The resulting photo scale was 600 feet per inch. At this scale, the 18-inch circular targets had only a 60-micrometre dimension, and could barely be seen with the naked eye. If their locations had not been known, they could not have been identified. Furthermore, it was impossible to distinguish one target configuration from another even under 20 times magnification. This test indicated that white was the best target color, and that a larger photo scale was needed.

Considering the risk of wind, ripples, and sun reflections, and adding a safety factor, a scale of 400 feet per inch was selected. At this scale the entire area of interest could not be covered with a single photo. Rather, a minimum of four photos were required.

The final flight plan, shown in Figure 3, was adopted. Note that standard stereo coverage of all of the area of interest was not obtained. This was suitable in this special circumstance, however, because the lake surface upon which targets floated was basically flat and of known elevation.

CONTROL POINTS

In order to obtain an acceptable photogrammetric solution, reliable ground control points with good geometry were necessary. Ten ground control points were used. Four artificial control points were placed along the northeast part of the shore line where no natural planimetric features were available. Their locations are shown in Figure 3. In other parts of the lake, natural planimetric features such as piers were used for the remaining six control points.

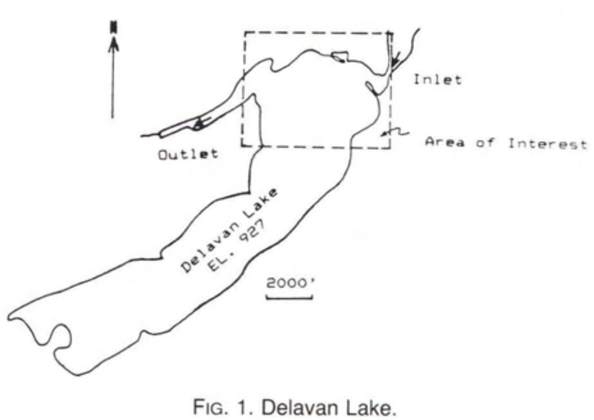

FIG. 1. Delavan Lake.

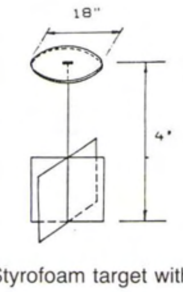

FIG. 2. Styrofoam target with drogue.

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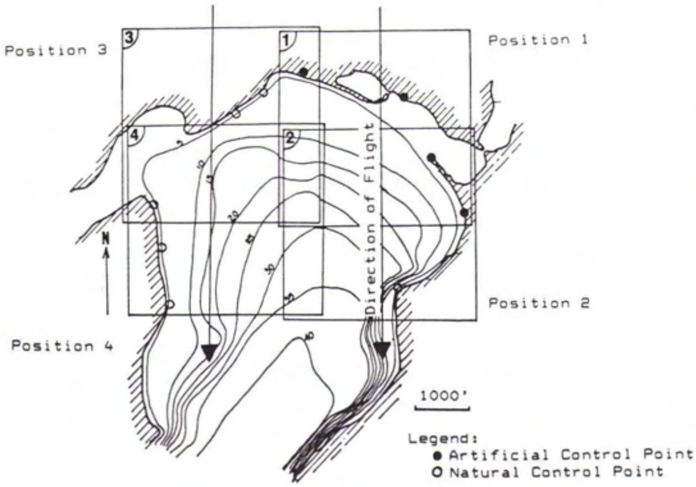

FIG. 3. Final flight plan.

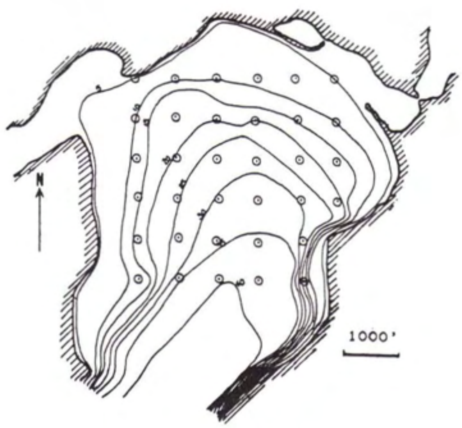

FIG. 4. Target placement.

TARGET PLACEMENT AND FLIGHT

Targets were placed in the lake just before photographing. An attempt was made to create an approximately 750-foot grid pattern, as shown in Figure 4. At each grid intersection, a surface target and a subsurface one were placed. Additional targets were placed along the east shore line because the wind direction on that day was westerly. Also, a cluster of surface targets were placed at one location to test the dispersion. In total, 60 surface and 44 subsurface targets were placed.

The aircraft flew from north to south, covering the area in two strips of two photographs per strip. Photography was repeated each five minutes, and continued for 2 hours (from 10 A.M. to 12 P.M.). A total of 22 repetitions were made, each consisting of four photographs.

CONTROL SURVEY

The control survey was performed after photographing. Theodolites were used for angle measurements, and an EDM for distances. For angles, every control station was occupied and each other station was sighted to obtain large amounts of redundancy. For distances, two stations were occupied and all other stations were sighted from those stations.

Solar observations were performed to establish the azimuth of the control network. The elevations of the control stations above the lake surface were also measured.

MENSURATION AND DATA REDUCTION

Even though the targets had been placed in a grid pattern, one of the most difficult parts of the data reduction was to keep track of paths of targets through all 22 photographic repetitions. This was due to the time lapse between photos, and the different speeds and travel directions of surface and subsurface targets. By pre-examination of the water speed on the day of photography, an approximate velocity of 0.5 ft/sec was observed for surface targets and 0.1 ft/sec for subsurface targets. Thus, a target's traveling distance in the 5-minute time lapse would be 150 feet for surface targets and 30 feet for subsurface targets. This information assisted in identifying corresponding targets in each repetition.

A position accuracy of approximately $\pm$ 5 ft for targets was considered satisfactory for this project. This value was arrived at because a 5-foot positional error would only affect velocities by approximately ± 0.02 ft/sec, and this was acceptable. Considering this level of required accuracy, it was felt that photo coordinate measurements could be made on paper prints using a tablet digitizer. This could not only achieve the desired results, but also enable rapid and efficient measurements to be made. For each photo, the fiducials, control points, and targets were digitized using an Hitachi 27 by 27-inch digitizer interfaced with an IBM PC. This digitizer has been described in an earlier paper by Montgomery and Wolf (1986). The data were then processed through an analytical photogrammetric system to obtain the desired results.

Three programs were developed for this problem. The first, called PRELIM, obtained preliminary values for input to the second, called CORREC, which corrected the ground coordinates of targets and generated new photo coordinates of targets. Then the last program BUNDLE, solved the simultaneous bundle problem. These programs are summarized below.

(1) Program PRELIM performed a two-dimensional affine coordinate transformation to convert digitizer coordinates to the photo coordinate system using calibrated fiducial coordinates. It then computed a space resection for each photo to obtain the six camera parameters for input as initial approximations to the bundle adjustment. Following this, it solved the space intersection problem to calculate preliminary target positions. This was a one-photo space intersection which solved the collinearity condition equations for preliminary X and Y coordinates of targets assuming the elevation of the lake surface to be zero. These were used as initial values for velocity vector calculations. Finally, the program performed a velocity vector computation based on preliminary X and Y coordinates of all targets of the 22 repetitions, together with the time lapse information.

(2) Program CORREC corrected the preliminary ground coordinates of targets of photos of positions 2, 3, and 4 (see Figure 3) so that the corrected locations corresponded to the instant of exposure of the photo of position 1. This was necessary because the next program, BUNDLE, presumes that images in all the four photos used in the solution are stationary, but the targets in this instance were moving. Then, using these corrected ground coordinates of targets and camera parameters from the preliminary space resection, revised photo coordinates for each photo were generated by substitution of these data into the collinearity condition equation.

(3) Finally, a simultaneous bundle program, BUNDLE, was applied with these revised photo coordinates. The camera parameters and corrected ground coordinates were used as initial approximations for the program. This program produced a set of X and Y coordinates of each target at the time of exposure of the first photo of each of the 22 repetitions. From the 22 sets of coordinates, final velocity vectors were computed. Table 1 below lists a sample of results. A graphic rendition of all results was obtained by using a computer to plot the final coordinates of each target for each repetition. This showed their movements across the lake. A CAD system was used to make the plot, and Figure 5 shows the surface targets.

CONCLUSION

Overall, it is believed that aerial photography as a method of measuring surface water velocity is more efficient and econom-

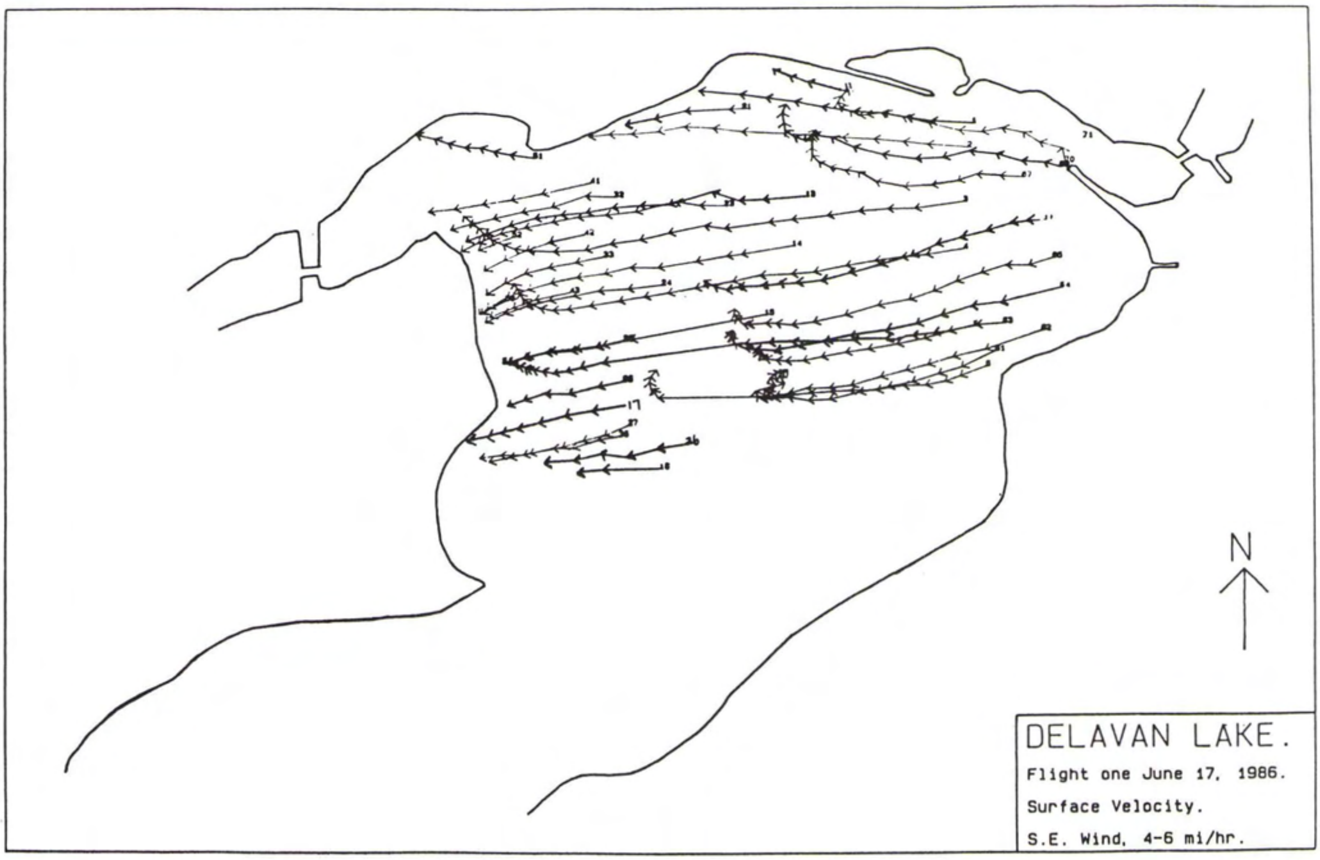

FIG. 5. Final surface current map.

TABLE 1. EXAMPLE OUTPUT OF THE VELOCITY CALCULATION PROGRAM

Repetition	X (ft)	Y (ft)	Time (hr:min:sec)	Distance (ft)	Bearing (deg)	Velocity (ft/s)
Target 1						
3	3713.9	3802.9	0 17 50	220.4	285.6	0.54
4	3501.7	3862.4	0 24 40	226.3	276.0	0.51
5	3276.6	3886.0	0 32 3	273.7	283.0	0.58
Target 202						
Repetition	X (ft)	Y (ft)	Time (hr:min:sec)	Distance (ft)	Bearing (deg)	Velocity (ft/s)
3	4036.6	3484.3	0 17 50	87.7	290.6	0.21
4	3954.5	3515.2	0 24 40	89.3	289.7	0.20
5	3870.5	3545.4	0 32 3	99.1	291.1	0.21

ical than other possible ways. Of special consideration, it enables relatively accurate, large area current studies to be simultaneously accomplished. Photogrammetry also enables suitable accuracies to be attained in determining water velocities. In this project, accuracies of ±5 feet were desired. The computed positional mean standard deviations in X and Y were 3.2 ft and 3.0 ft, respectively, which met our objective. Of course, higher accuracies could have been obtained by using film diapositives and a precise comparator.

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