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RATE OF WATER REPLACEMENT IN A BAY OF LAKE MENDOTA, WISCONSIN

REID A. BRYSON

and

ROBERT A. RAGOTZKIE

Department of Meteorology

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The Experiment

During the spring of 1952, the fall of 1953, and the summer of 1954 a line of eight stations was established across the mouth of University Bay, Lake Mendota, Wisconsin. The currents at various depths were measured by the drag method (Putnam et al, 1949) using either a taffrail log or a rangefinder for distance measurement. The velocity components normal to the line of stations, i.e. into or out of the bay, were computed and processed to yield horizontal divergence rates for the entire bay at each level.

The divergence of a layer is the rate of replacement of that layer by export or import across the mouth of the bay. If there is net loss of water in a layer by outflow across the mouth of the bay, this must be compensated by vertical motion or replacement within the bay. If there is net gain in the layer by inflow, some water in the bay must be displaced vertically, downward in the case of the surface layer. In either case there is compensating flow at depth to maintain a constant water level in the bay. For ease of interpretation, the time required for complete replacement of a layer will be used rather than the rate.

Replacement Times

Replacement times varied from about three hours to more than six hundred hours (Table 1). It must be borne in mind, however, that the replacement times are computed from a series of current measurements made over an hour or so. A replacement time of six hours does not mean necessarily four complete renewals of the water in one day, for the rate can and does change rather

Table 1

Summary of replacement times and mean outward velocity components for University Bay

Date	Mean velocity divergence x 10^{-5} x $sec.^{-1}$	Thickness of surface layer used (meters)	Replacement time (hours)	Mean outward velocity cm./sec. 1 m	Wind Velocity mph	Direction
1 July 54	+1.67	1	17.0	+1.30	6-8	W
30 June 54	-0.44	1	77.0	- .34	13	NW
29 June 54	+3.34	1	9.7	+2.60	14	W
28 June 54	+3.83	1	7.2	+2.98	8	S
26 June 54	-0.23	1	120.0	- .189	13	NW-NE
25 June 54	+7.00	1	4.0	+5.45	15	SSW
24 Nov. 53	+3.30	1	8.4	+2.57	15	NW
24 Apr. 52	-4.34	1	6.5	-3.38	15	NE
23 Apr. 52	-8.70	1	3.2	-6.78	15-20	ENE
22 Apr. 52	-2.26	1	12.0	-1.76	3-5	N
19 Nov. 53	+3.64	1	7.6	+2.84	10-12	S
30 Oct. 53	+2.64	2	10.0	+2.22	15	SW
7 July 54	-5.49	5	5.1	-3.56	12	N
8 July 54	-0.04	5	690.0	+ .23	3	WNW
9 July 54	+1.39	5	20.0	+1.75	3	S
16 July 54	-0.78	5	36.0	- .20	1-5	N

rapidly with the wind. For example, on 8 July 1954 the computed replacement time for the upper five meters of water was 214 hours, but 24 hours later the replacement time had changed to 20 hours.

The rate of replacement of the upper layers is a function of the down-bay component of the wind, for the replacement time is proportional to the mean velocity of the water across the bay mouth, and this in turn is related linearly to the down-bay component of the wind (Figure 1). At greater depths wind effects are reduced and pressure gradients play a greater role (Bryson and Suomi, 1952) as indicated by the smaller variability of replacement times at ten meters (Table 2).

Table 2

Replacement times in hours at various depths

Date	1 m	2 m	5 m	10 m
7 July 1954	5.5	3.5	8.3	10.1
8 July 1954	82.0	252.0	57.0	7.9
9 July 1954	10.0	32.0	46.0	20.0
14 July 1954	---	---	25.0	17.0
16 July 1954	90.0	14.0	695.0	17.0

The Picnic Point Jet

The authors had observed on many occasions prior to this study that there existed a narrow strip of rapidly moving water leaving University Bay along the south side of Picnic Point, the peninsula bounding the bay on the north. This phenomenon is clearly shown on the profiles of water velocity components

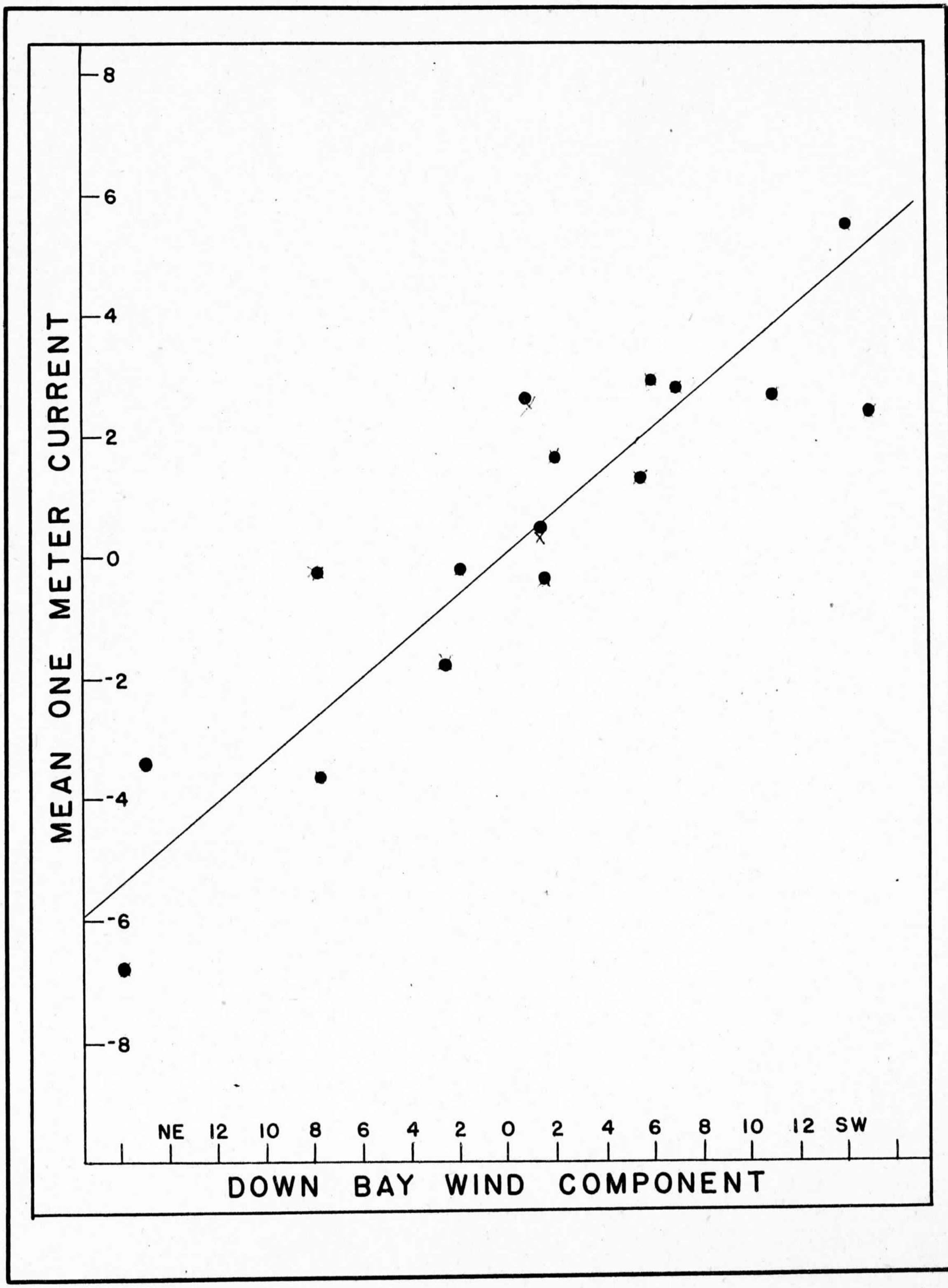

Fig. 1. -- Down-bay wind component versus mean 1 meter current. The winds were measured at Truax Field, near Lake Mendota, but are probably representative for the lake.

normal to the bay mouth (Figures 2-5). That this is not an isolated occurrence is indicated by the fact that it is present on the mean velocity profile as well (Figure 6). It has been identifiable on every profile of velocity which has been made.

Unlike the mean velocity normal to the bay mouth, the velocity of the jet is found to be proportional to the cross-bay wind component, but the factor of proportionality seems to be different with a north-west component than with a southeast component (Figure 7). Furthermore the core of the jet is closer to Picnic Point with a southeast component and more distant with a northwest component. In the latter case there is often a narrow countercurrent between the jet and the shore of Picnic Point. These facts suggest that different processes are operative in the two cases.

As may be seen from the mean chart (Figure 6) there is normally an anticyclonic eddy in University Bay. The evidence presented in this paper and others (Bryson and Suomi 1952, Ragotzkie and Bryson 1953) shows that this eddy is wind driven, and thus the outward flow on the north side of the bay would be proportional to the wind.

In the case of a northwest wind the main portion of the lake and University Bay behave as two separate basins from the point of view of stratification. The isotherms are depressed and the thermocline sharpened downwind, while rising towards the surface upwind. Therefore off the tip of Picnic Point a discontinuity is observed for it is upwind for University Bay and downwind for the main portion of the lake (Bryson and Suomi 1952, Figure 2). The tilt of the surface across the discontinuity would produce a slope current into the bay and the relative current due to the slope of the isotherms would be

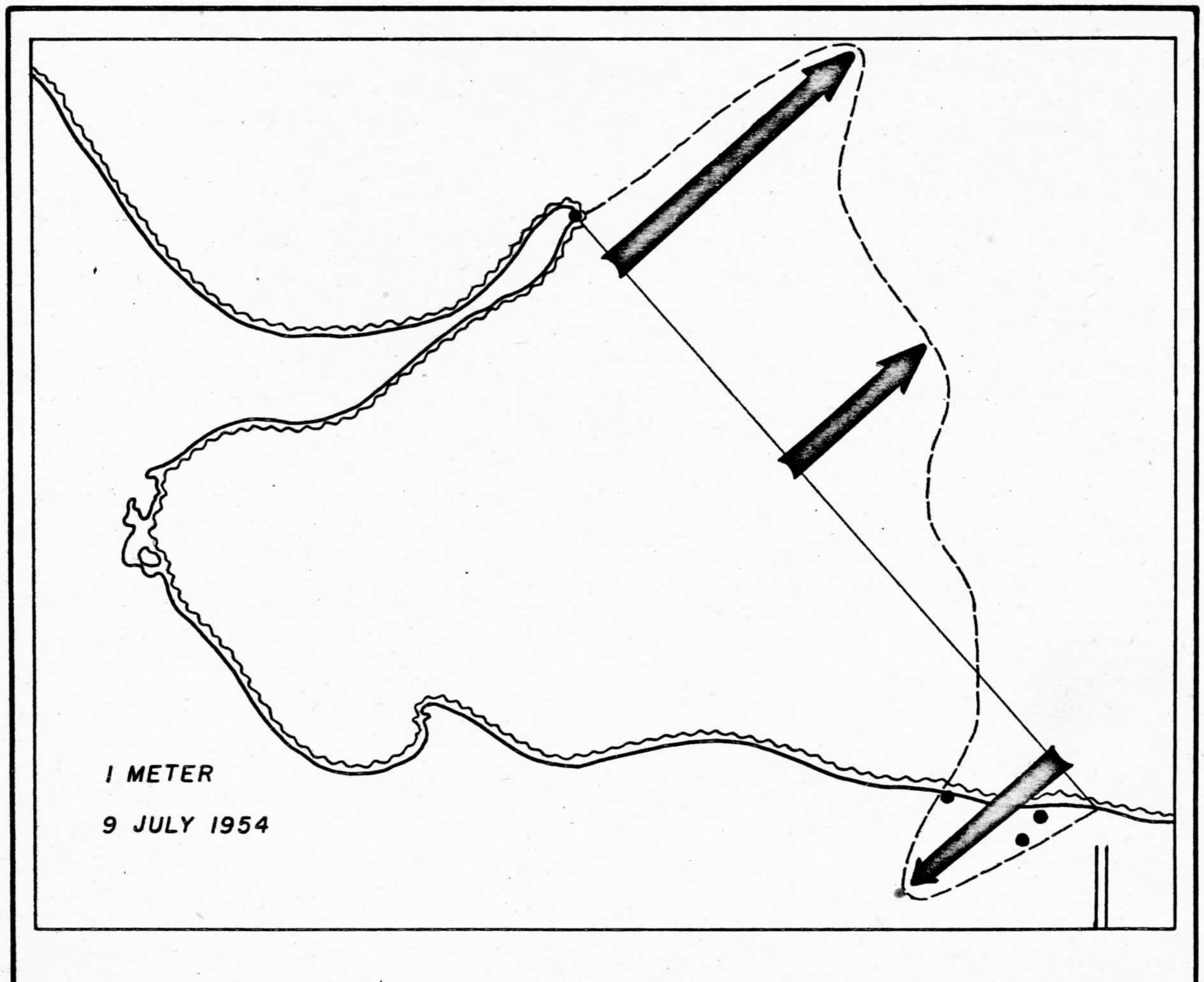

Fig. 2. -- Current profile at 1 meter depth. 9 July 1954. Transport per ten thousand seconds is shown.

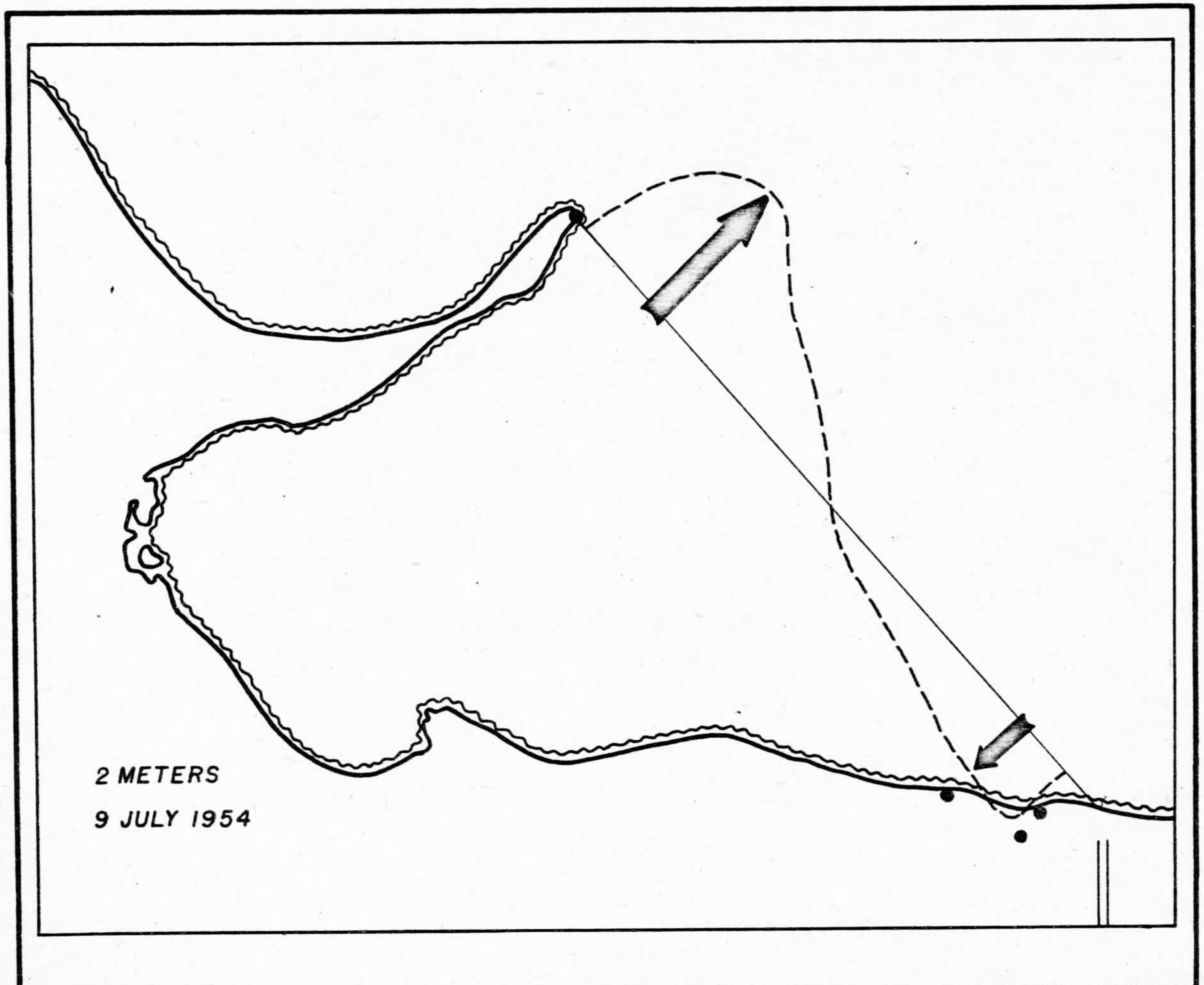

Fig. 3. -- Current profile at 2 meter depth. 9 July 1954. Transport per ten thousand seconds is shown.

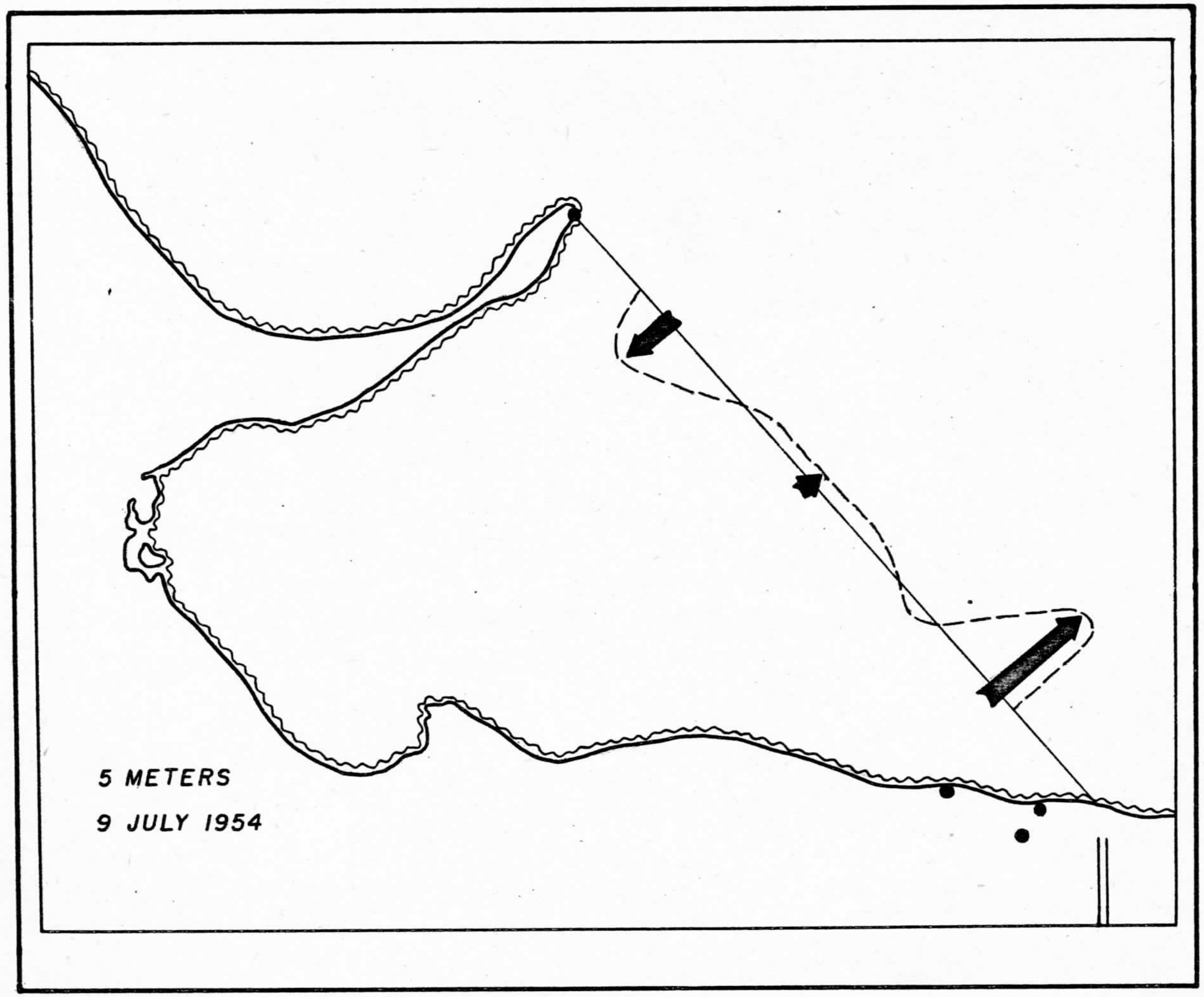

Fig. 4. -- Current profile at 5 meter depth. 9 July 1954. Transport per ten thousand seconds is shown.

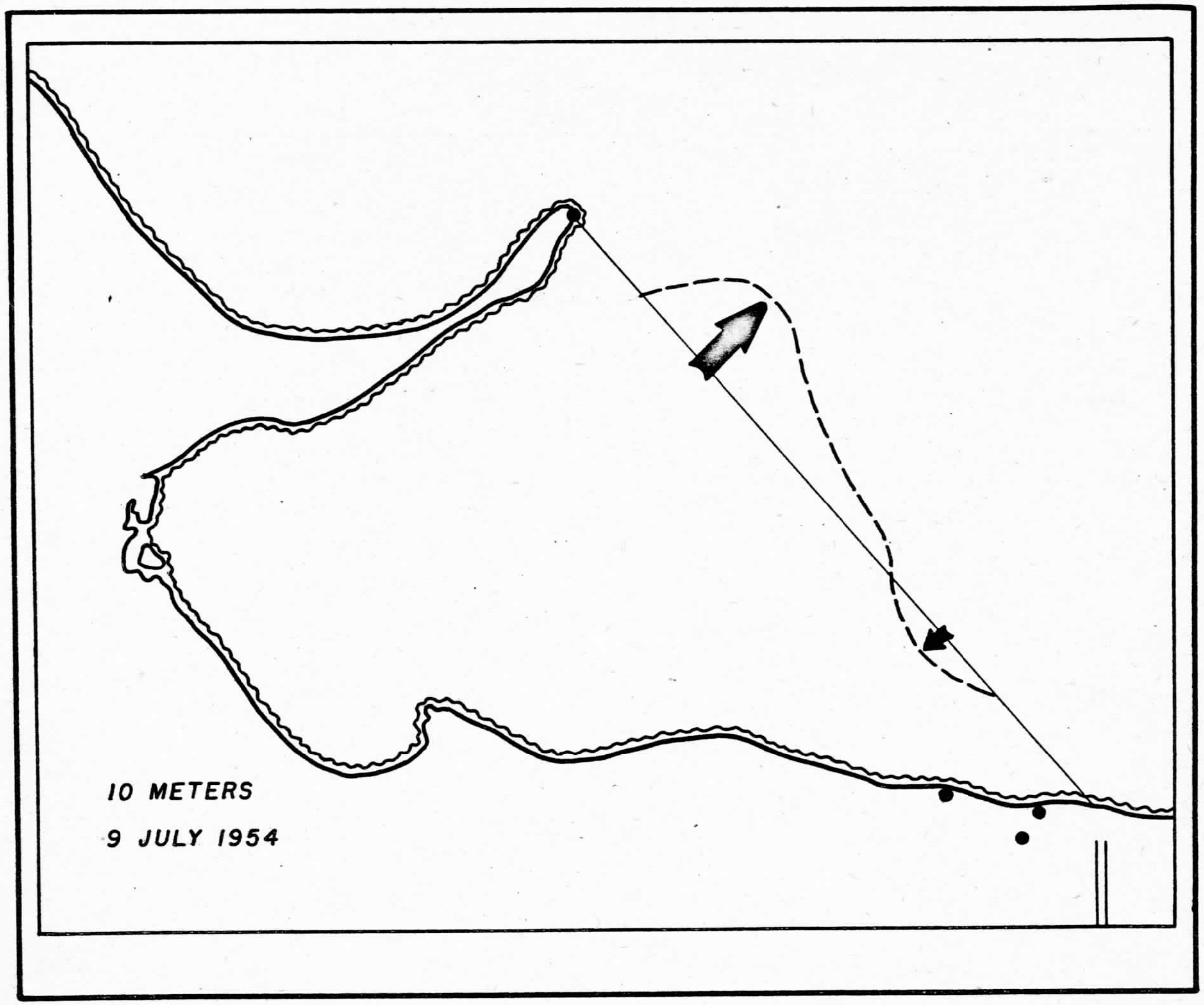

Fig. 5. -- Current profile at 10 meter depth. 9 July 1954. Transport per ten thousand seconds is shown.

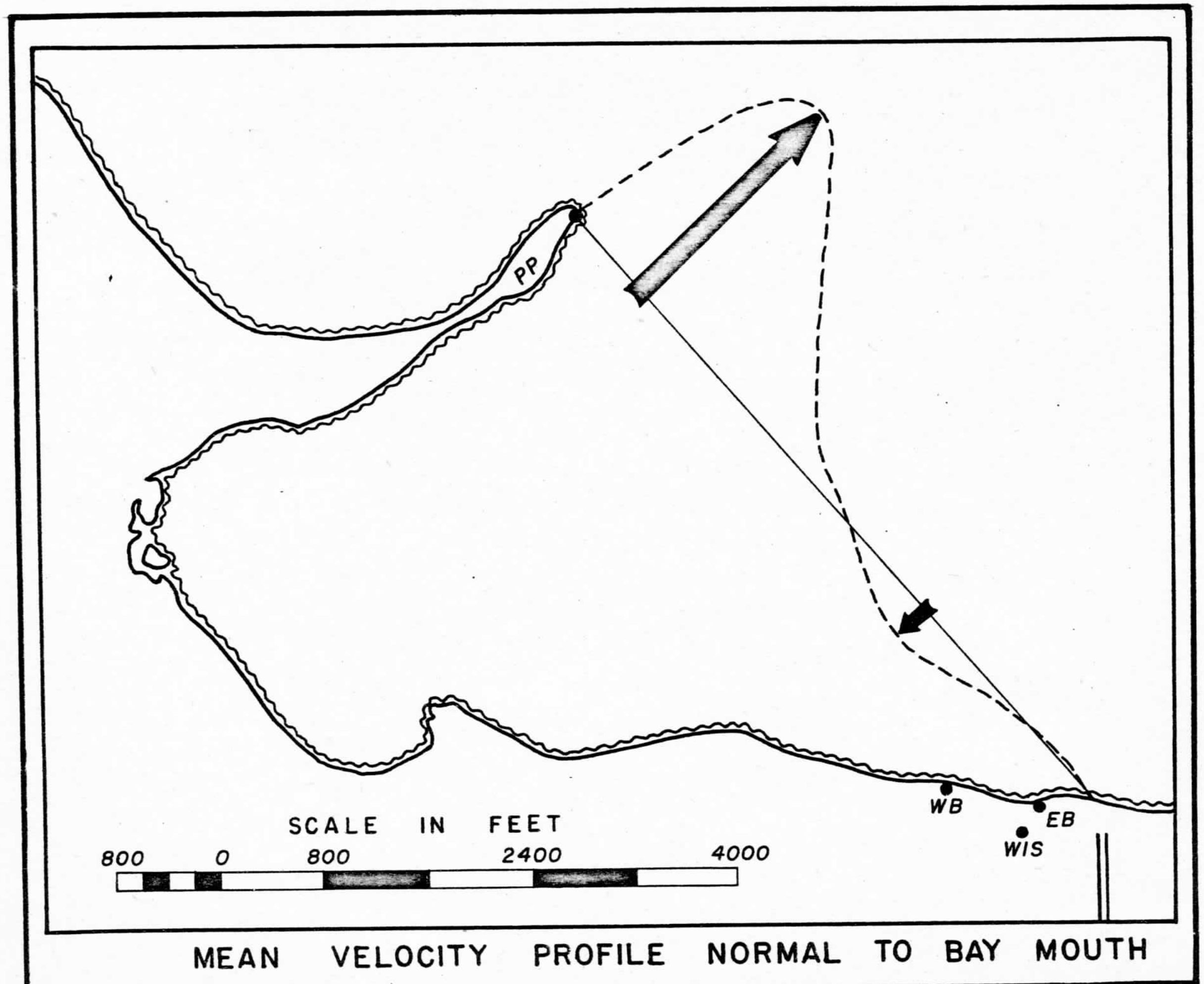

Fig. 6. -- Mean current profile at 1 meter depth. Transport per 10000 seconds is shown.

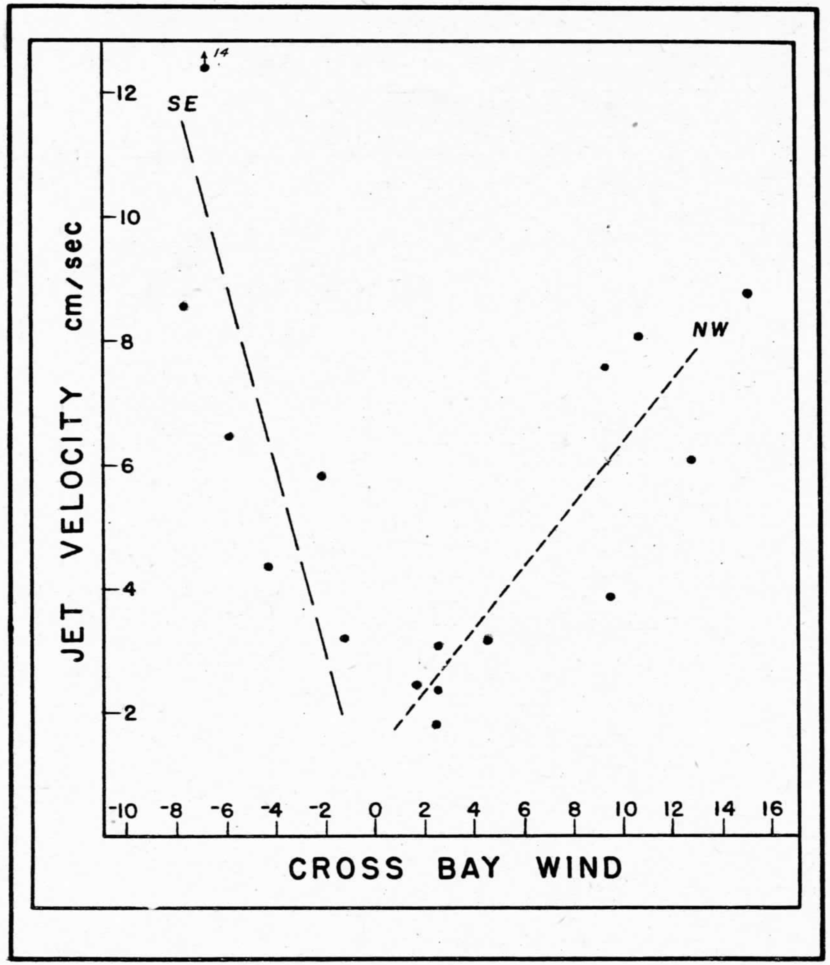

Fig. 7. -- Cross-bay wind component versus jet velocity relative to mean current. 1 meter depth. Wind as in figure 1.

similarly directed. This effect would run counter to the normal outflow and is the probable cause of the countercurrent and reduced jet velocity near Picnic Point. With a southeast wind the slope and relative currents at the discontinuity would add to the normal wind driven outflow in the neighborhood of the Point, thus giving higher velocities in that region. (Figure 7)

Horizontal Eddies

Referring back to Figure 6 it may be seen that there is another mode of water replacement, i.e. by purely horizontal exchange--export on one side of the bay and replacement by import on the other side. This effect is superimposed on the divergence discussed in previous sections of this paper.

In University Bay, replacement of this type usually is accomplished by maximum outflow along Picnic Point, in and along the jet which has been described; and secondarily in a narrow region along the south shore of the bay. In the surface layer the location of the region of maximum inflow varies with the maximum outflow velocity along Picnic Point. Such a pattern suggests an eddy whose size varies with the velocity around the eddy, a characteristic of inertia circles. To examine the possibility of inertial flow the following procedure was adopted: From the arithmetic average of the velocity maxima into and out of the bay, the radius of the appropriate inertia circle was calculated. Half the distance between the two velocity maxima was taken as the observed radius.

The correspondence between the calculated and observed radii is an indication, at least, of whether inertial flow actually occurs (Figure 8).

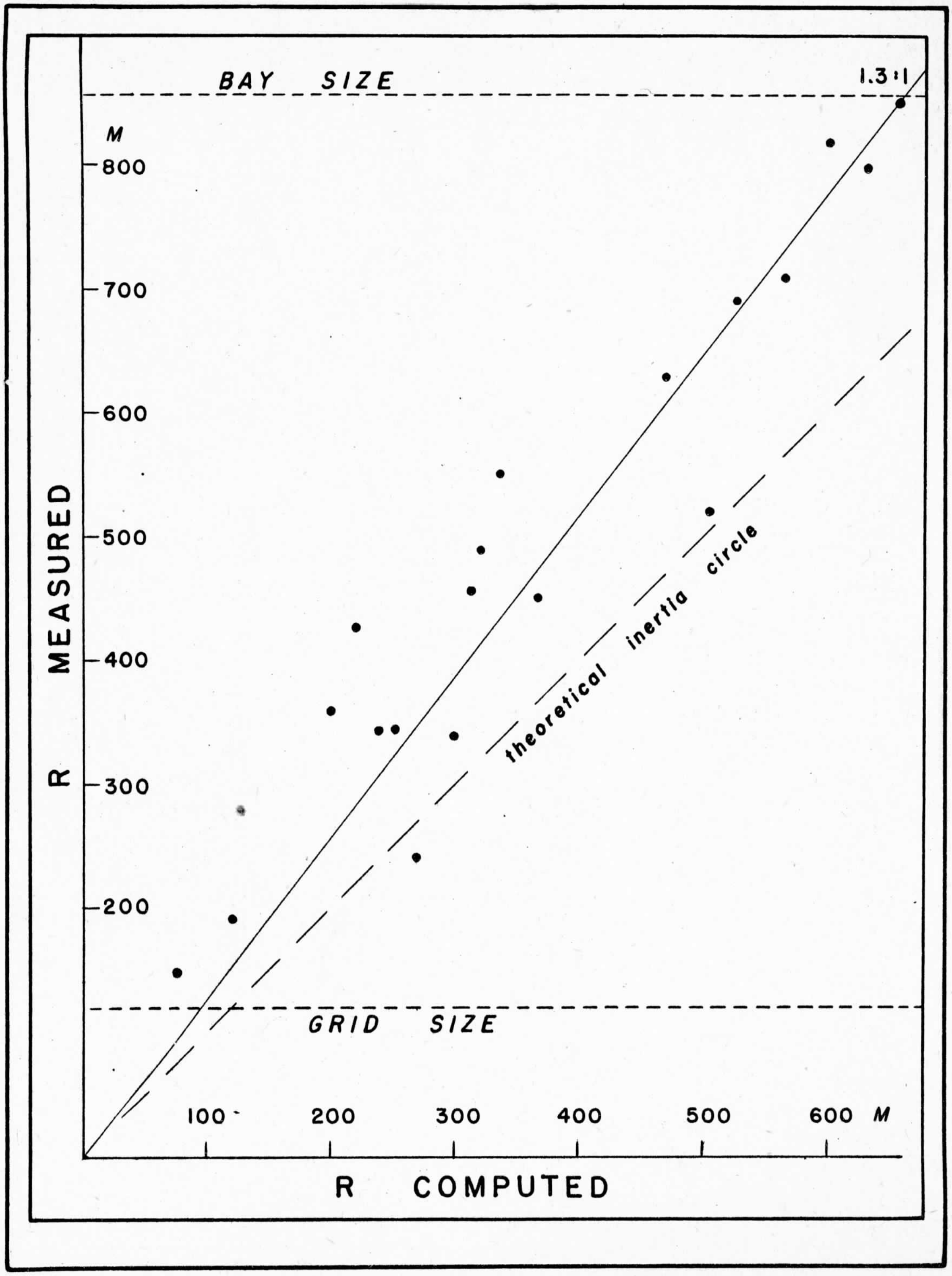

Fig. 8. -- Computed radius of inertia circle with velocity given by maximum outflow and inflow velocities versus measured radius (i.e. half the distance between regions of maximum outflow and inflow.)

The good agreement found between the two radii indicates that high inflow and outflow velocities are associated with large eddies (or gyres if the word may be used in a limnological sense) which are largely inertial in character in the surface layers. This affords us an estimate of the rate of replacement by strictly horizontal exchange. For the two halves of an inertia circle or gyre to exchange requires one-quarter pendulum day or 8-1/2 hours at the latitude of Madison, Wisconsin.

Application to Plankton Sampling

The high but variable replacement times for University Bay clearly illustrate that from a circulation point of view the lake and the bay do not tend to be separated. Vertical motions are shown to be necessarily present for the occurrence of net replacement of a layer by the divergence mechanism. Whenever and wherever vertical motions occur the zooplankton and probably the phytoplankton are affected. It has been shown by the authors (Ragotzkie and Bryson, 1953) that concentration of zooplankton occurs in regions of sinking water (horizontal convergence) and dispersal occurs in regions of upwelling (horizontal divergence). These changed population densities may be transported by horizontal currents far from the region where concentration or dispersal occurred. The Picnic Point jet would be a very effective vehicle for rapid horizontal transport of plankton out of the bay. Large eddies or gyres which exist in the mouth of the bay would also serve as a means for transporting concentrated masses of plankton or water relatively poor in plankton into and out of the bay. As all of these mechanisms are usually operating at the same time, the situation is far from simple.

Complex though they are, the movements of the water in a bay system such as this do tend toward certain patterns which are explicable on a reasonable physical basis. Circulation patterns may repeat under similar wind conditions, and occasionally part of the pattern is present under practically any wind situation, e.g. the Picnic Point jet. Recognition and consideration of these patterns, even in a qualitative way, before taking plankton samples at one or several stations would prevent many of the "odd" or misleading results so often associated with this branch of limnology.

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Bryson, R. A. and V. E. Suomi. 1952, "The circulation of Lake Mendota", Trans. Amer. Geophys. Union, 33:707-712.

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