Use of an Acoustic Doppler Current Profiler (ADCP) to Measure Hypersaline Bidirectional Discharge

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Abstract

The U.S. Geological Survey measures the exchange of flow between the north and south parts of Great Salt Lake, Utah, as part of a monitoring program. Turbidity and bidirectional flow through the breach in the causeway that divides the lake into two parts makes it difficult to measure discharge with conventional streamflow techniques. An acoustic Doppler current profiler (ADCP) can be used to more accurately define the angles of flow and the location of the interface between the layers of flow. Because of the high salinity levels measured in Great Salt Lake (60-280 parts per thousand), special methods had to be developed to adjust ADCP-computed discharges for the increased speed of sound in hypersaline waters and for water entrained at the interface between flow layers.

Introduction

Great Salt Lake, Utah, is a terminal lake with historical salinity levels ranging from about 60 to 280 parts per thousand (Stephens, 1999, p. 2). The lake is divided into a north and a south part by a causeway, which functions as a semipermeable dam. About 60 percent of the lake volume is contained south of the causeway. Because nearly all surface-water inflow to the lake is to the southern part, the north part of the lake is about 0.15 to 1.0 meter lower in altitude and two to three times more saline than the south part. Water can flow through the causeway in two 15-foot-wide box culverts, a 300-foot-wide breach, and the semipermeable rock-fill material. The two culverts are submerged when the altitude of the lake surface is above 4,198 feet. The breach is an open channel. Hypersaline water flows through the causeway and at times consists of two separate layers of flow, of different salinity, moving in opposite directions (fig. 1). Density gradient and water-surface altitude drive bidirectional flow between the two parts of the lake.

The U.S. Geological Survey (USGS) measures the exchange of flow between the two parts of the lake, through the breach, as part of a monitoring program. Initially, measurements of these flows were made by using conventional streamflow techniques, with a Price AA vertical-axis current meter suspended by a cable. However, water turbidity made it difficult to determine horizontal angles of flow and the location of the interface between the layers of flow. Results with the Price AA meter were poor, and measured discharges generally were considered estimates.

In an attempt to more accurately define angles of flow and the location of interface between the layers, an acoustic Doppler current profiler (ADCP) was used. An ADCP is an electronic instrument used to measure water velocity. The instrument

transmits acoustic signals into the water column. When the frequency of the transmitted signals is compared with the frequency of backscatter signals reflected off particles in the water, the velocity of the particles, and hence the water, can be calculated. By mounting an ADCP to a boat and measuring the velocity within a series of water columns (ensembles, fig. 1) along a transect of the flow channel, data needed to compute bidirectional discharge can be obtained.

Data Collection

The USGS collects flow data at the breach in the Great Salt Lake causeway with an RD Instruments (RDI) 1200 Workhorse Sentinel ADCP mounted on a boom that is mounted to a 12-foot inflatable boat (fig. 2). The Sentinel ADCP is relatively small (0.4 meter long by 0.2 meter wide) and lightweight (13.0 kilograms). It is designed for long-term deployment, with internal memory and battery, but can be used as a direct sensor for measurement of stream velocity and cross-sectional area. The boat is crewed by a pilot and an ADCP operator. The ADCP measures discharge by dividing a transect of the measurement cross section into a series of water columns (ensembles), then dividing each water column into vertical layers (cells), and then calculating the average velocity and area for each cell (fig. 1).

The data-collection process begins by setting the measurement boundary conditions for the ADCP through modification of a configuration file. Parameters such as cell depth, blanking distance, instrument modes, and depth of transducer below the water surface must be defined before the ADCP begins collecting data. As cell depth decreases, the vertical definition of the velocity within the ensemble increases, but the errors in velocity measurement also increase. A 10-centimeter cell depth is used for measurement at the breach to define the velocity within each of the two shallow layers of flow. The blanking distance moves the location of the first cell away from the transducer head to allow the transmit circuits time to recover before the receive cycle begins. The instrument mode changes to a different transducer pulse for each different flow condition. Bottom mode 5 and water mode 8, which are for shallow-water measurements, are used. The depth of the transducer below the water surface is needed to compute the total depth of the water column. Within the configuration file there is an option to set the salinity at the transducer heads, but during data acquisition, the salinity is set to zero. Adjustments for salinity are made when the data are processed.

Choosing the proper location to make a measurement transect is critical to obtaining good data. The selection of an acceptable transect location at the breach is limited to the channel of flow, which is bound by the northern and southern edges of the causeway (fig. 3). The transect location must also be far enough from piers to avoid turbulence, which interferes with the ADCP signal processing. Finally, the location must be chosen where the flow is not too shallow (less than 1 meter) or too slow (less than 0.05 meters per second) to be measured by the ADCP. Generally the outermost edge of the causeway is used for the measurement cross section (fig. 3).

A measurement transect is made by navigating the boat in a straight line normal to the direction of flow, while the ADCP collects depth, distance, and velocity data. A measurement generally begins and ends at the location closest to each bank where depth is greater than 1 meter. The distance from the shore to the ADCP must be measured at the beginning and end of each transect and is used later to estimate the discharge of the edges

of the measurement cross section (fig. 1). A minimum of four transects are made, which later are averaged together during data processing.

Salinity is measured to adjust for the speed of sound in hypersaline water and to adjust the total measured discharge for water entrained at the interface between the layers of flow and returned to the part of the lake from which it originated (fig. 4). Salinity is measured at vertical sets along the measurement transect, along with a representative measurement from each side of the causeway.

Data Processing

Once the depth, area, velocity, and salinity data are collected in the field, they are processed with the RDI WinRiver software and a spreadsheet developed by USGS personnel to compute bidirectional discharge. The ADCP uses the speed of sound in the water at the transducer heads to compute depth and velocity. During data collection the ADCP is configured for the speed of sound in fresh water, but the speed of sound increases with temperature, salinity, and depth as shown in equation 1 (Brekhovskikh and Lysanov, 1982, p. 1).

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016z \quad (1)$$

where:
1449.2 = speed of sound in fresh water, in meters per second;
    c = the speed of sound, in meters per second;
    T = the temperature, in degrees Celsius (°C);
    S = salinity, in parts per thousand (ppt); and
    z = depth, in meters.

Equation 1 is valid for $0°C \leq T \leq 35°C$, $0 \leq S \leq 45$ ppt, and $0 \leq z \leq 1,000$ meters. The WinRiver software will compute the speed of sound for saline waters, but only up to a salinity level of 40 ppt. Because salinity levels in Great Salt Lake are always greater than 60 ppt and no information could be found pertaining to the speed of sound in water with a salinity level greater than 45 ppt, the assumption was made that the linear relation between salinity and the speed of sound extends beyond 45 ppt. To compute the speed of sound for ADCP measurements made in Great Salt Lake, equation 1 and the field-collected salinity data are used.

The computed speed of sound is entered into the WinRiver software, which recomputes depth, distance, velocity, and discharge. If bidirectional flow exists, the WinRiver software will subtract the layer of lesser flow from the layer of greater flow, producing a net discharge through the measurement transect. Because obtaining total flow in each direction is the purpose of the measurements at the breach, a method was developed to compute these flows from the depth, distance, and velocity data processed by the WinRiver software. The data is exported in ASCII format from WinRiver and then imported into a spreadsheet developed by USGS personnel that computes bidirectional discharge.

To obtain the discharge through the transect, the discharge through each individual cell within each ensemble is computed first. The WinRiver output used by the spreadsheet to compute bidirectional flow for one ensemble is shown in cells A2 through D21, and cells J23 through J25 of table 1. All other cells in table 1 are computed.

Discharge through each cell in an ensemble is computed from the WinRiver output by using equations 2–12:

Depth at center of top cell $\qquad\qquad\qquad A1 = \dfrac{A2}{4}.$ $\qquad\qquad$ (2)

Because of limitations of the ADCP, the flow velocity must be estimated at the top of each ensemble. The velocity of the top cell, which extends from the surface to the first cell measured by the ADCP, is estimated by using equations 3 and 4:

(East velocity component of top cell) $\qquad B1 = 0.3 * \ln\left[e^{|3.33*B2|} \dfrac{J27 - A1}{J27 - A2} \right]$ $\qquad$ (3)

$\qquad\qquad\qquad$ where if B2 = 0, then B1 = 0, and
$\qquad\qquad\qquad\qquad$ if B2 < 0, then B1 = -B1;

(North velocity component of top cell) $\qquad C1 = 0.3 * \ln\left[e^{|3.33*C2|} \dfrac{J27 - A1}{J27 - A2} \right]$ $\qquad$ (4)

$\qquad\qquad\qquad$ where if C2 = 0, then C1 = 0, and
$\qquad\qquad\qquad\qquad$ if C2 < 0, then C1 = -C1.

The horizontal velocity direction of the top cell is assumed to be the same as that of the cell just below it:

(Horizontal velocity direction of top cell) $\qquad\qquad D1 = D2,$ $\qquad\qquad$ (5)

(Horizontal velocity magnitude) $\qquad\qquad\qquad E_{row} = \sqrt{B_{row}^2 + C_{row}^2}.$ $\qquad\qquad$ (6)

Because it is the component of the velocity normal to the measurement cross section that is used for computing discharge, vertical velocity measured by the ADCP is assumed to be accounted for with entrained flow and horizontal velocity is corrected to include only the component normal to the cross section:

(Horizontal angle correction coefficient) $\qquad\qquad F_{row} = \cos(D_{row} - J22),$ $\qquad$ (7)

(Velocity magnitude normal the cross section) $\qquad G_{row} = E_{row} * F_{row},$ $\qquad$ (8)

(Cell width) $\qquad\qquad\qquad\qquad\qquad J26 = \dfrac{J25_{J22+1} - J25_{J22-1}}{2}$ $\qquad\qquad$ (9)

$\qquad\qquad\qquad$ where $J25_{J22+1}$ = the distance from the origin of the next ensemble, and
$\qquad\qquad\qquad\qquad$ $J25_{J22-1}$ = the distance from the origin of the previous ensemble;

(Area of top cell)
$$H1 = J26 * \frac{A2}{2}, \qquad (10)$$

(Cell area, rows 2-20)
$$H_{row(2-20)} = J26 * \frac{A_{row+1} - A_{row-1}}{2}, \qquad (11)$$

where $H_{row(2-20)}$ = any cell in column H, from row 2 to 20, of table 1;
A_{row+1} = the cell in column A below cell A_{row}; and
A_{row-1} = the cell in column A above cell A_{row};

(Discharge through cell)
$$I_{row} = G_{row} * H_{row} \qquad (12)$$

where
A1 = cell A1 of table 1, (B1 = cell B1, etc.);
E_{row} = any cell in column E of table 1, (F_{row} = any row in column F, etc.).

The average depth of the interface between the two layers of flow (cell J27) are entered in the appropriate location on the spreadsheet (table 1). The ADCP measures the total depth of the ensemble (cell J24) but cannot measure the velocity at the bottom of the ensemble. The velocities of the bottom cells (rows 13 and 14), which extend from the last cell measured by the ADCP (row 12) to the streambed (cell J24), are estimated to be the same as the velocity of the last cell measured by the ADCP (cell G12).

Once discharge is computed for each cell, within every ensemble of the transect, positive and negative cells are summed separately to obtain the total discharge for each layer of flow through the transect. Next the discharge through the shallow edges of the measurement cross section, which the ADCP cannot measure, is manually estimated on the basis of the first and last ensembles of the transect. The total discharge in each direction through the measurement cross section is then computed from the discharge through the transect and through the shallow edges.

The final step in computing the exchange of flow between the two parts of the lake is adjusting the total discharge in each direction through the measurement cross section for water entrained at the interface and returned to the part from which it originated (fig. 4):

$$Q_{S \to S} = \left[Q_l * \left(\frac{\rho_l - \rho_N}{\rho_S - \rho_N} \right) \right], \qquad (13)$$

$$Q_{N \to N} = \left[Q_u * \left(\frac{\rho_u - \rho_S}{\rho_N - \rho_S} \right) \right], \qquad (14)$$

$$Q_u = Q_{S \to N} + Q_{S \to S} + Q_{N \to N} \quad \text{or} \quad Q_{S \to N} = Q_u - Q_{S \to S} - Q_{N \to N}, \qquad (15)$$

$$Q_l = Q_{N \to S} + Q_{N \to N} + Q_{S \to S} \quad \text{or} \quad Q_{N \to S} = Q_l - Q_{N \to N} - Q_{S \to S} \qquad (16)$$

where

Q_u = Discharge through the upper flow layer at the measurement cross
        section, in cubic meters per second;

Q_l = Discharge through the lower flow layer at the measurement cross
        section, in cubic meters per second;

$Q_{S \to N}$ = Discharge from the south part to the north part of the lake, in cubic
        meters per second;

$Q_{N \to S}$ = Discharge from the north part to the south part of the lake, in cubic
        meters per second;

$Q_{S \to S}$ = Discharge from the south part of the lake, entrained at the interface, and
        returned to the south part, in cubic meters per second;

$Q_{N \to N}$ = Discharge from the north part of the lake, entrained at the interface, and
        returned to the north part, in cubic meters per second;

ρ_u = Salinity of the upper flow layer at the measurement cross-section, in ppt;

ρ_l = Salinity of the lower flow layer at the measurement cross-section, in ppt;

ρ_S = Salinity of the main body of the south part of the lake, in ppt; and

ρ_N = Salinity of the main body of the north part of the lake, in ppt.

Equations 13-16 are used to compute the amount of flow through the measurement cross section that is actually exchanged between the two parts of the lake. First, the flow entrained at the interface and returned to the part from which it originated ($Q_{S \to S}$ and $Q_{N \to N}$) is calculated by using the mass balance found in equations 13 and 14. Next the exchange of flow between the two parts of the lake ($Q_{S \to N}$ and $Q_{N \to S}$) is computed by subtracting the entrained flow from the discharge measured in each layer at the measurement cross section (Q_u and Q_l). To obtain final values, the discharges $Q_{S \to N}$ and $Q_{N \to S}$ from a minimum of four transects are averaged.

Conclusion

     Measurements of bidirectional flow through a breach in a causeway across Great Salt Lake, Utah, have been made by using both a Price AA current meter and an RDI 1200 kilohertz Workhorse ADCP. With the Price meter, water turbidity made it difficult to determine horizontal angle corrections and the location of the interface between the layers of flow. Results with the AA meter were poor and measured discharges generally were considered estimates. An ADCP, which measures water depth and velocity with sound waves, was used to more accurately define the angles of flow and the location of the interface between the layers of flow. After adjusting data collected with the ADCP for the increased speed of sound in hypersaline waters, and for water entrained at the interface between layers of flow, a better representation of the flow dynamics through the breach was obtained. The resulting discharge measurements are considered more accurate than the measurements previously made with the Price AA meter.

Disclaimer
     The use of trade names in this report does not imply endorsement by the U.S. Geological Survey.

References
Brekhovskikh, L.M., Lysanov,Y., 1982, Fundamentals of Ocean Acoustics: Berlin, New York, Springer-Verlag, 245 p.

Stephens, D.W., 1999, Great Salt Lake, Utah: U.S. Geological Survey Water-Resources Investigations Report 99-4189, 4 p.

Figures and Tables
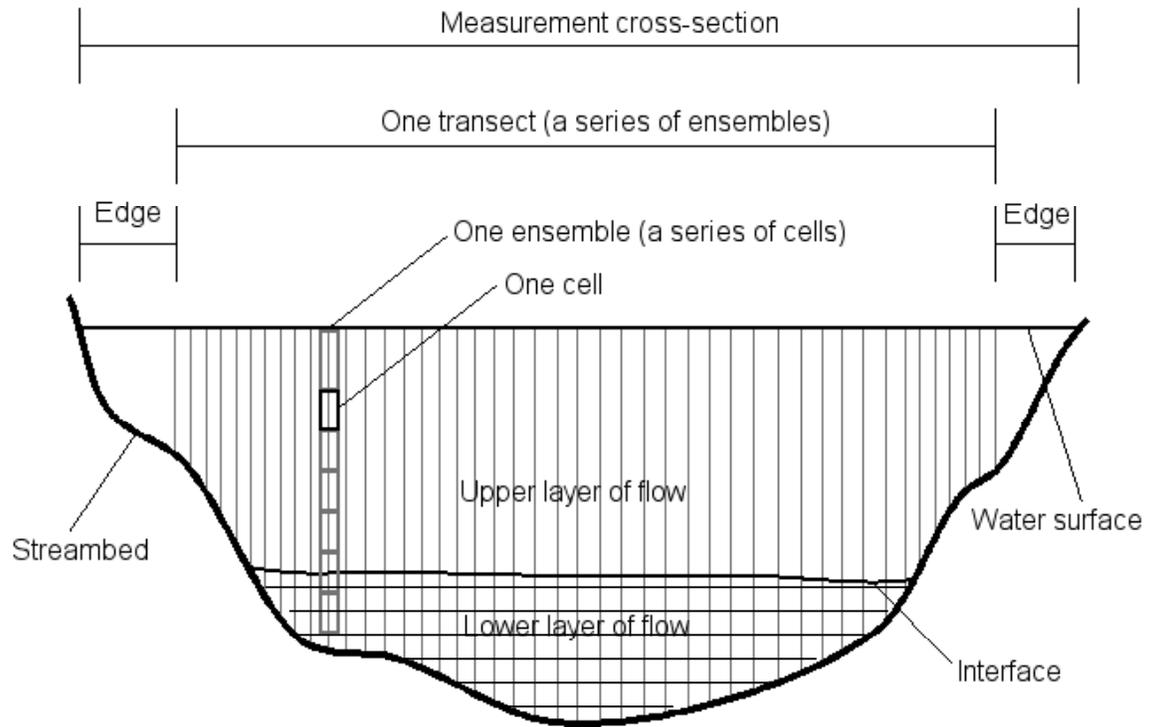
Figure 1. Schematic diagram of an acoustic Doppler current profiler (ADCP) measurement of flow through the breach in the causeway on Great Salt Lake, Utah.
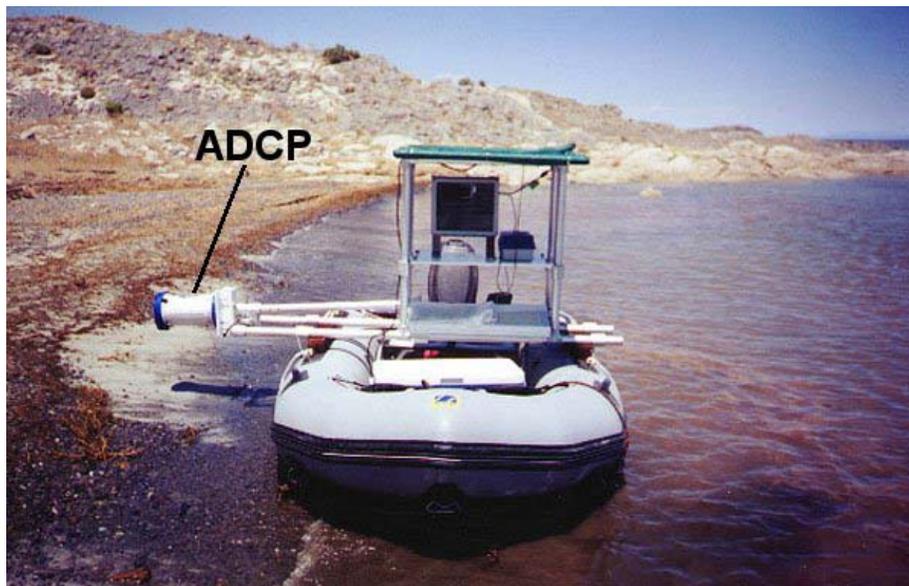
**Figure 2.** Acoustic Doppler current profiler (ADCP) mounted to an inflatable boat.
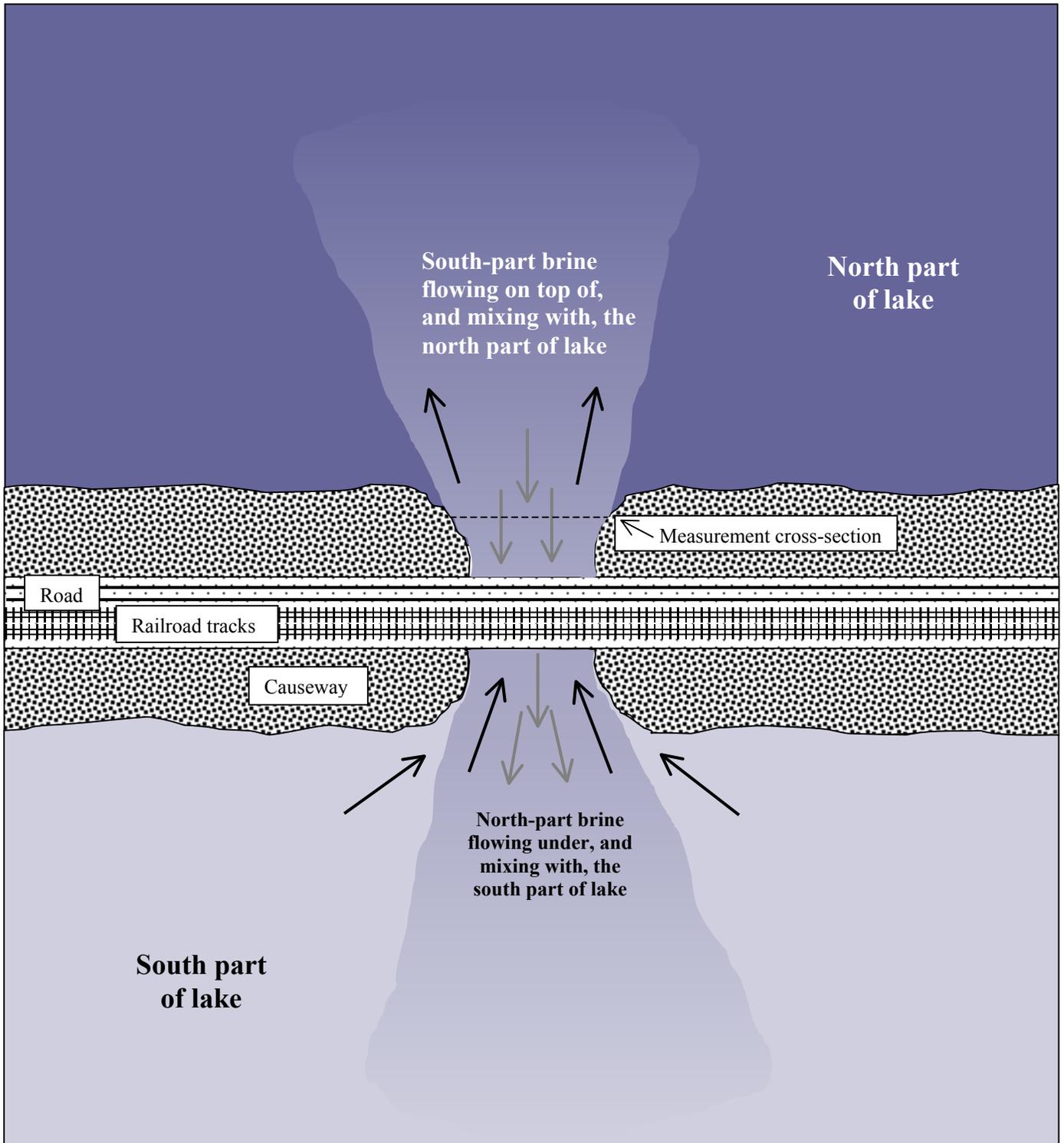
Figure 3. Diagram of breach in the causeway of Great Salt Lake, looking down.

Bridge piers

Water Surface

$$Q_u = Q_{S \to N} + Q_{S \to S} + Q_{N \to N}$$
$$\rho_u$$

South part of lake ρ_S

$Q_{N \to N}$

Measurement cross-section

Interface

North part of lake ρ_N

$Q_{S \to S}$

$$Q_l = Q_{N \to S} + Q_{N \to N} + Q_{S \to S}$$
$$\rho_l$$

Floor of the breach
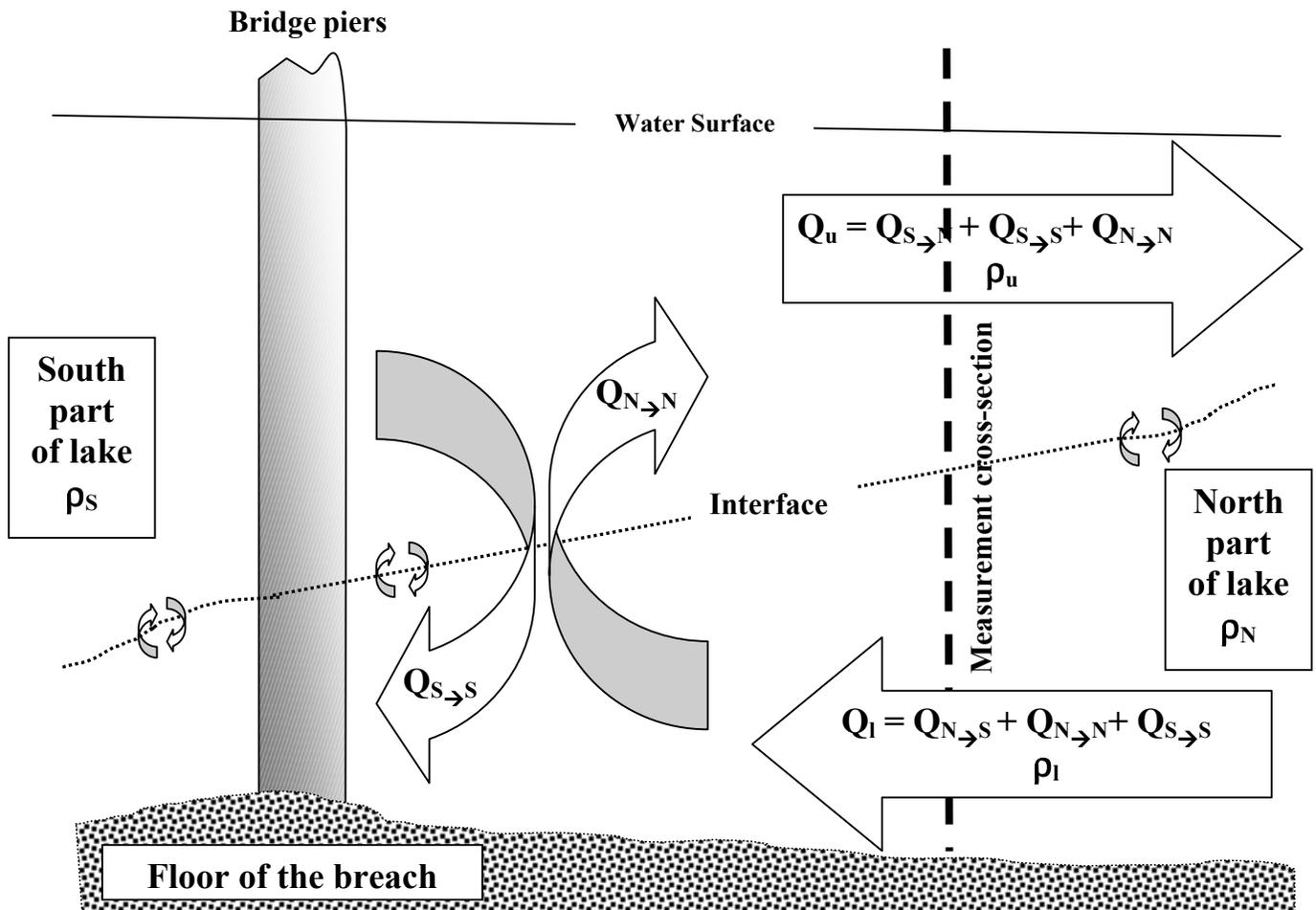
Q_u	= Discharge through the upper flow layer at the measurement cross section
Q_l	= Discharge through the lower flow layer at the measurement cross section
$Q_{S \to N}$	= Discharge from the south part to the north part of the lake
$Q_{N \to S}$	= Discharge from the north part to the south part of the lake
$Q_{S \to S}$	= Discharge from the south part of the lake, entrained at the interface, and returned to the south part
$Q_{N \to N}$	= Discharge from the north part of the lake, entrained at the interface, and returned to the north part
ρ_u	= Salinity of the upper flow layer at the measurement cross section
ρ_l	= Salinity of the lower flow layer at the measurement cross section
ρ_S	= Salinity of the main body of the south part of the lake
ρ_N	= Salinity of the main body of the north part of the lake

Figure 4. Diagram of flow through breach in the causeway of Great Salt Lake, looking west.

Table 1. Example ensemble from U.S. Geological Survey spreadsheet used to compute bidirectional discharge from RD Instruments WinRiver ASCII-Out data file

	A	B	C	D	E	F	G	H	I	J
1	0.15	0.000	1.134	0	1.134	0.96	1.089	0.165	0.180	
2	0.59	0.000	0.732	0	0.732	0.96	0.703	0.192	0.135	
3	0.69	-0.061	0.610	354	0.613	0.98	0.603	0.055	0.033	
4	0.79	-0.122	0.396	342	0.415	1.00	0.414	0.056	0.023	
5	0.89	0.000	0.640	359	0.640	0.97	0.618	0.056	0.035	
6	0.99	0.000	-0.061	188	0.061	-0.91	-0.056	0.056	-0.003	
7	1.09	-0.091	-0.366	193	0.377	-0.87	-0.330	0.055	-0.018	
8	1.19	-0.152	-0.152	219	0.216	-0.57	-0.124	0.055	-0.007	
9	1.29	-0.152	-0.244	208	0.288	-0.72	-0.207	0.056	-0.012	
10	1.39	-0.091	-0.335	195	0.348	-0.86	-0.298	0.056	-0.017	
11	1.49	0.061	-0.244	167	0.251	-1.00	-0.251	0.056	-0.014	
12	1.59	0.030	-0.213	171	0.216	-0.99	-0.214	0.055	-0.012	
13	1.69	-	-	-	-	-	-0.214	0.055	-0.012	
14	1.79	-	-	-	-	-	-0.214	0.056	-0.012	
15	1.89	-	-	-	-	-	-	-	-	
16	1.99	-	-	-	-	-	-	-	-	
17	2.09	-	-	-	-	-	-	-	-	
18	2.19	-	-	-	-	-	-	-	-	
19	2.29	-	-	-	-	-	-	-	-	
20	2.39	-	-	-	-	-	-	-	-	
21	2.49	-	-	-	-	-	-	-	-	
22							Downstream direction			344
23							Ensemble number			61
24							Total depth			1.82
25							Distance from origin			12.16
26							Cell width			0.56
27							Interface depth			0.98

Column A = depth below surface in meters;

Column B = east velocity component [east (+) / west (-)], in meters per second;

Column C = north velocity component [north (+) / south (-)], in meters per second;

Column D = horizontal velocity direction, in degrees from magnetic north;

Column E = horizontal velocity magnitude, in meters per second;

Column F = horizontal angle correction coefficient;

Column G = velocity magnitude normal to the measurement cross section, in meters per second;

Column H = cell area, in square meters;

Column I = discharge through cell, in cubic meters per second [downstream (+), upstream (-)];

Column J = as described in table, row 22 is in degrees from magnetic north and rows 24 - 27 are in meters; and

- = missing or invalid data for cell.