Stratified Reservoir Density Flows Influenced by Entering Streamflows

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Density stratification due to seasonal temperature variations in temperate zone lakes is a well-known occurrence. Variations of fluid density in a reservoir, coupled with environmental effects, give rise to internal flow patterns that can have a considerable effect on reservoir water quality. In determining how such currents might be controlled, major efforts in the past have been directed toward examining withdrawal current effects on the internal reservoir flows. However, little concern has been directed to characterizing the influences of entering streamflow on the current patterns of a stratified reservoir. This paper discusses several important hydrodynamic effects related to cold or dense streamflow waters entering a stratified reservoir having less dense surface strata.

ENTRANCE MIXING

When a streamflow enters an impoundment at its particular temperature, it mixes and descends to an elevation at which the resident water has the same density (or temperature). Exchanges of thermal energy within stratified lakes or reservoirs are closely coupled to the magnitude of hydrologic surface inflows and corresponding internal currents. It has been found that the entrance mixing effect changes thermal regime simulation predictions for heat budget analysis of reservoirs as significantly as changes by orders of magnitude of the vertical effective diffusion coefficient for heat transport [*Slotta*, 1970; *Huber and Harleman*, 1968; *Ryan and Harleman*, 1971]. Assumptions are made somewhat arbitrarily in the presently available simulation models regarding the mixing of reservoir surface waters and inflowing streams.

Experimental work also has led to the conclusion that entrance mixing of entering streamflows is more significant than was previously considered [*Slotta et al.*, 1969; *Ryan and Harleman*, 1971]. It has been found that changes in the amount of entrance mixing have a very strong effect on model reservoir temperature profiles. Examples of entrance mixing or entrainment rates of typical inflows are listed by *Ryan and Harleman* [1971] as inflow at surface (i.e., warm water), 50% entrainment; inflow at intermediate depth, 200% entrainment; and inflow at reservoir bottom (i.e., cold water), 500% entrainment. Fieldwork is necessary to fill the gap in selecting physically reasonable values for simulation applications using entrainment and stream-pool mixing ratios.

INTERNAL CURRENTS

Laboratory experiments conducted at Oregon State University (1969) showed that reproducible major current patterns develop as streamflows enter a stratified reservoir [*Slotta et al.*, 1969]. The laboratory model reservoir was 7.62 meters (25 feet) long and was filled in gradient salt solution layers to provide the desired density stratification. The experimental setup is sketched in Figure 1, and flow parameters are indicated. Flow field current patterns and velocity measurements were determined photographically. Time-lapse movies of an experiment would compress a 2-hour study to a 3-min movie for review. The major currents found in the laboratory model are indicated in Figure 2.

Selective withdrawal releases from the laboratory model were programed to balance the incoming streamflows. The selective withdrawal current was observed as a major current that had a coupling action to the inflows. Inflow and mixing currents occurred at levels different from the level of the withdrawal current.

Conclusions drawn from these laboratory studies were:

1. Two possible main inflow currents can be expected in a stratified reservoir.
2. The upper inflow current increased in magnitude as the streamflow Reynolds number

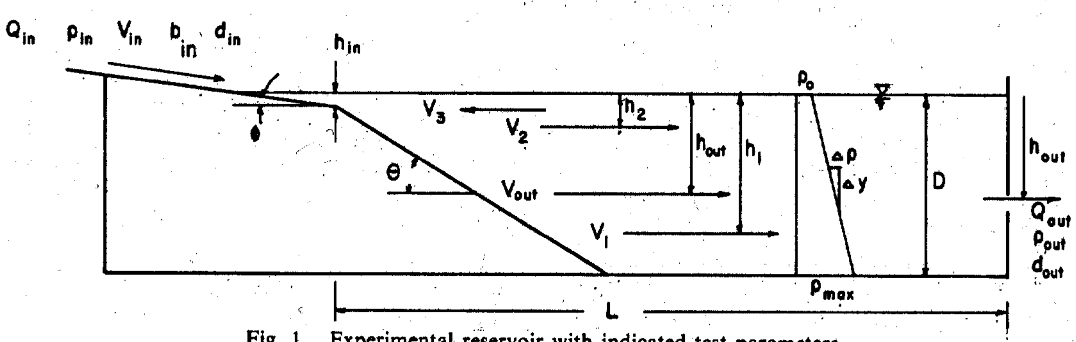

Fig. 1. Experimental reservoir with indicated test parameters.

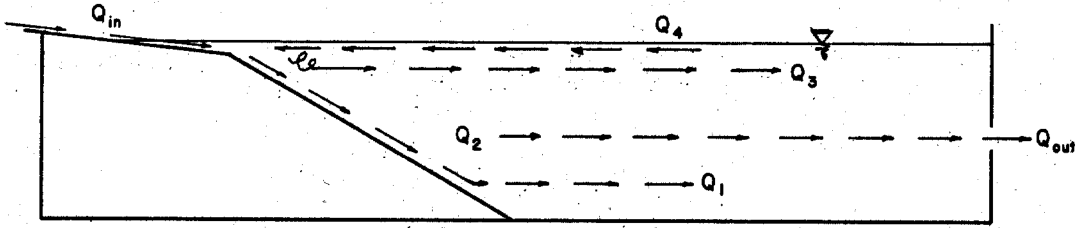

Fig. 2. Major current patterns.

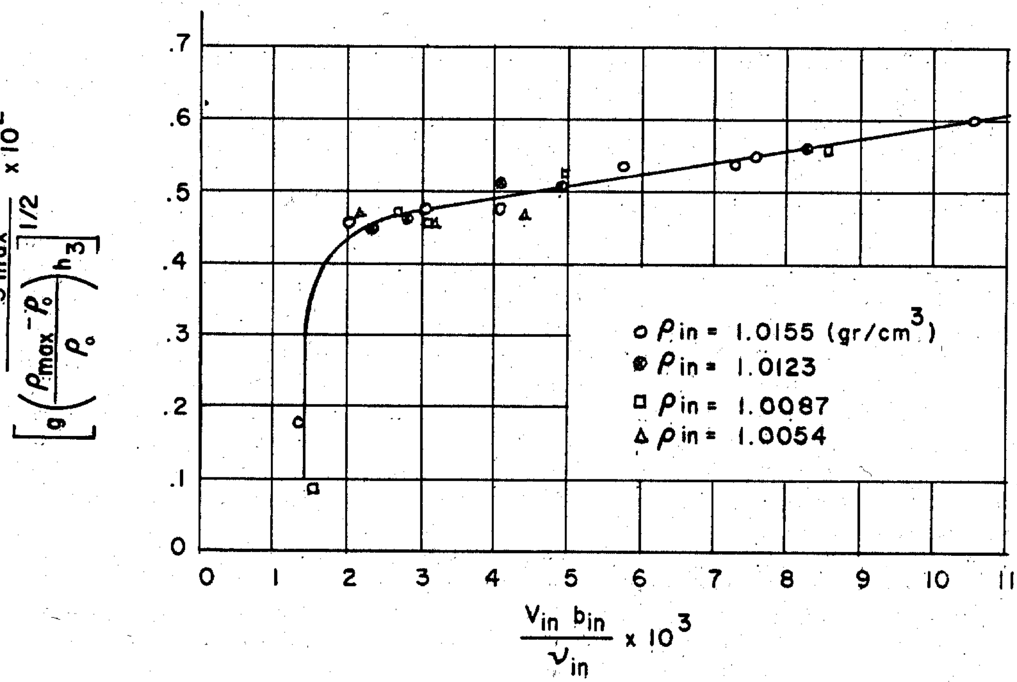

Fig. 3. Densimetric Froude number of Q_3 versus streamflow Reynolds numbers.

was increased. An empirical relation between the densimetric Froude number and Reynolds number was obtained. However, the elevation of the upper inflow current was independent of stream velocity and density (see Figure 3).

3. The lower inflow current was present only at a streamflow Reynolds number below a critical value. The elevation of the lower inflow current was dependent on the entering density and mixing that occurred at the stream mouth (see Figure 4).

4. Interaction and reinforcement of currents can be expected particularly when the effects of withdrawal releases are considered.

5. The influence of environmental factors (such as wind) is important in developing surface and seiche currents.

6. Topography and reservoir geometry have significant effects on internal reservoir currents.

Regarding experiments conducted at Froude scale with laminar flows to model actual reservoir currents, it can be related that the eddy scales of motion found in the hypolimnion of actual reservoirs are of the order of molecular scales. Thus the eddy diffusion coefficient for mass transport nearly approximates the eddy viscosity coefficient for these stable waters. Experiments conducted in the laboratory with large inflow turbulent discharges entering into a stratified pool showed spread phenomena similar to those obtained in the laminar flow experiments.

Predictions from lake and reservoir measurements give effective diffusion coefficients within hypolimnetic waters ranging from 0.1 to 10 cm²/sec [*Bella,* 1969; *Orlob and Selna*, 1970]. The validity of this model-prototype Froude scaling is limited by insufficient field evidence.

FIELD STUDIES

Field measurements of inflows to reservoirs are scarce. Some data on flow passage through the Tennessee Valley Authority (TVA) system have been reported by *Elder and Wunderlich* [1968]. Field measurements on Fontana Reservoir inflows, traced by dye concentrations, indicate interflows as expected from laboratory experiments.

The causes, sources, and means for controlling turbidity found in Hills Creek Reservoir, Oregon, are being studied by Oregon State University researchers. Clear, cold inflows entering this reservoir create an easily discernible interface with the turbid pool (see Figure 5). The turbidity interface shown in Figure 5 shows typical inflow currents as depicted in laboratory studies. It is hoped that research support can be obtained to

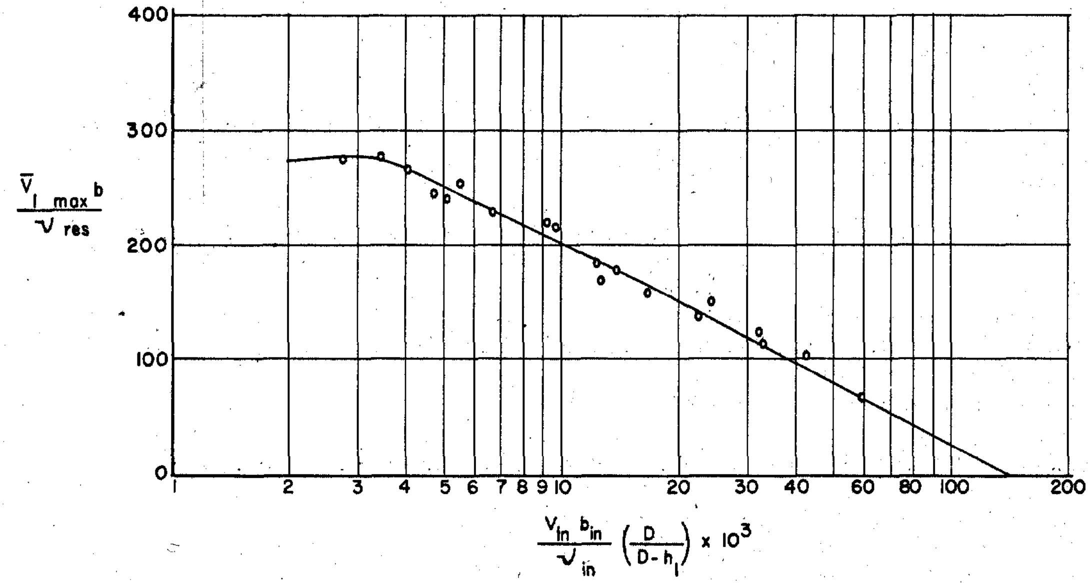

Fig. 4. Logarithmic plot of scaled streamflow Reynolds number versus the number of Q_1.

Fig. 5. Hills Creek Reservoir, Oregon, January 2, 1971. Entering water temperature is 4.4°C, and pool water temperature is 6.1°C.

possibly verify and substantiate through field studies the laboratory findings on inflow mixing and internal reservoir currents.

Near-surface and near-bottom light scattering (nepheloid) layers have been discovered in the oceans [*Ewing and Thorndike*, 1965; *Jacobs and Ewing*, 1969]. Mineral analysis of suspended particulate materials in freshwaters and seawaters has been useful in determining the cause and source of turbidity in these waters. Hopefully, our laboratory findings may eventually contribute to explain the mode of transport of suspended sediment within the seas and reservoir waters.

APPENDIX: MODEL RESULTS

$$V_{1\mathrm{max}} = \frac{\nu}{b}\left\{-0.5 \log \cdot \left[\left(\frac{V_{\mathrm{in}} b_{\mathrm{in}}}{\nu_{\mathrm{in}}}\right)\left(\frac{D}{D - h_1}\right)\right] + 365\right\}$$

(See Figure 3.)

$$V_{3\max} = \left[\left(\frac{\rho_{\max} - \rho_o}{\rho_{\max}}\right) h_3 g\right]^{1/2} \cdot \left(1.67 \times 10^{-4} \frac{V_{\text{in}} b_{\text{in}}}{\nu_{\text{in}}} + 0.42\right)$$

(See Figure 4.)

NOTATION

D, total reservoir depth;
ϕ, angle of inflow;
θ, reservoir bed slope angle;
h_{in}, depth of slope change;
h_{out}, depth of outlet;
L, length of reservoir;
b, width of channel;

Inflow

Q_{in}, inflow rate;
V_{in}, inflow velocity;
b_{in}, inflow width;
d_{in}, inflow depth;

Outflow

Q_{out}, outflow rate;
V_{out}, outflow velocity;
ρ_{out}, outflow density;
d_{out}, outflow diameter;

Ambient fluid

$\Delta\rho/\Delta\rho$, density gradient;
ρ_o, bottom density;
$\rho_{\max}$, bottom density;
g, gravitational acceleration;
ν, kinematic viscosity;
Q_1, low-level density current;
h_1, low-level current depth;
Q_2, selective withdrawal current;
h_2, current level;
Q_3, upper-level mixed current;
h_3, upper-level current depth.

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