HIDDEN FLOW PATTERNS IN RESERVOIRS

by Norman H. Brooks

The fluids around us – water and air – are almost always stratified according to their density. For many ordinary engineering problems dealing with strong motions on a relatively small scale (such as flow of water in a pipe, or the flow of air around the wing of an airplane) we may easily neglect the density stratification; the ordinary mechanics of homogeneous fluids apply. But when we consider weak motions in large bodies of fluid, the slight variation in fluid weight with depth (due to gradients of temperature or salinity) may profoundly alter the fluid motion.

When the density increases with increasing depth in a reservoir, or in the ocean, the stratification is stable; each parcel of fluid has its own position of stable equilibrium, and work is required to displace it either up or down. By contrast, in a homogeneous tankful of fluid no work is required to push a parcel of fluid from bottom to top because an equal and opposite displacement is induced. All water in a homogeneous body has *equal* potential energy or piezometric head, whereas density-stratified water does not.

Density stratification is found in most large man-made reservoirs, such as Lake Mead behind Hoover Dam. Two basic flow problems of interest to civil engineers are: (1) What happens to the river water entering the reservoir? (2) What happens when water is withdrawn through outlets in the dam?

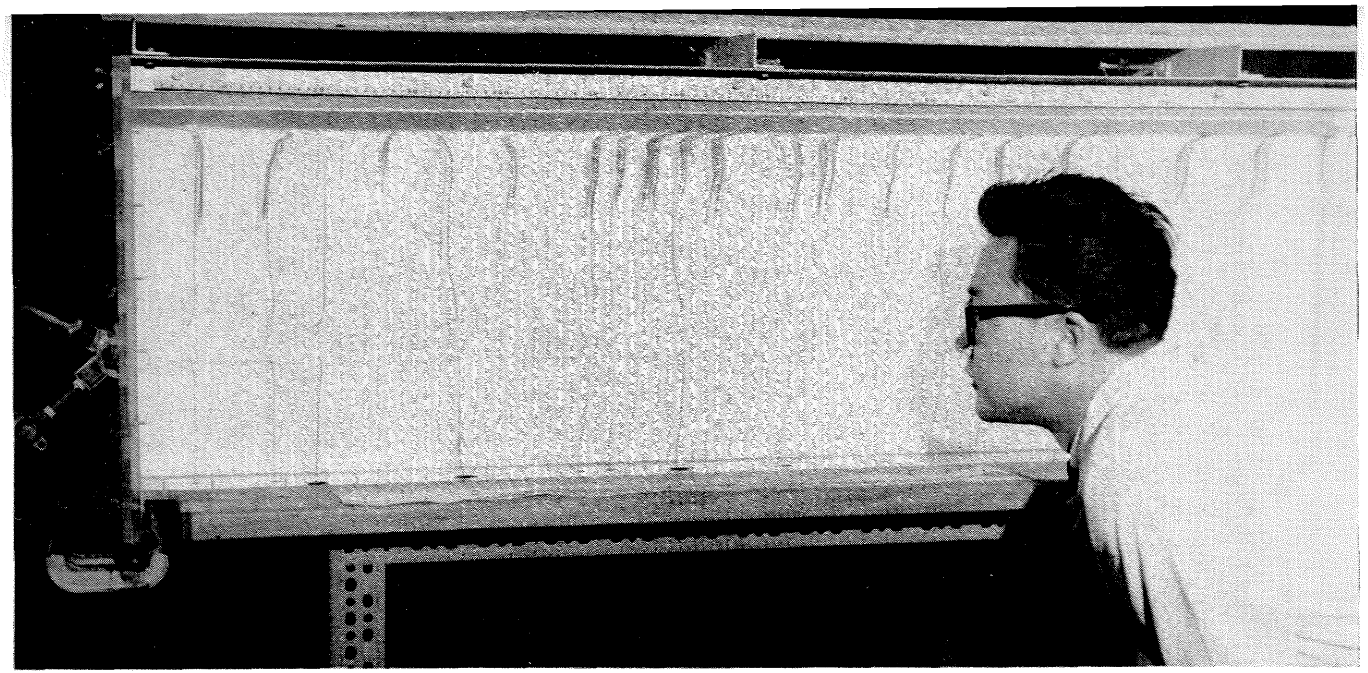
It has been found that river inflow is usually slightly denser than reservoir water because of its sediment load and colder temperature. Within a few years after the closure of Hoover Dam, a huge, submerged pool of muddy river water was found adjacent to the dam, proving that there was a definite current of this heavier river water along the bottom of the reservoir for 120 miles, from the river mouth to the dam.

A pioneering laboratory study of density currents at Caltech 25 years ago helped to clarify this phenomenon, and demonstrated many interesting features of these submerged underflows which are called density currents by the engineers, and turbidity currents by geologists. Because of the slight density difference between the underflow and the reservoir, the downward slope of the reservoir bottom provides the force to keep the current going, while vertical mixing between the layers is retarded by the stratification.

Density currents are to be found in many places. Surely you have felt the density current on your bare feet when you opened the refrigerator? And there are many examples in the atmosphere and the ocean. Geologists debate the question of whether turbidity currents are a major factor in the submarine movements of sediment or not.

The question of what happens when water is drawn from a reservoir is the subject of intensive research in the W. M. Keck Laboratory of Hydraulics and Water Resources at Caltech. In recent years it has been found at Grand Coulee Dam that the temperature of the Columbia River downstream of the dam could be partially controlled by selecting the level from which water was withdrawn from the lake – the coldest water coming from the deepest outlets.

Temperature control is important when the water is used for cooling, as it is at the atomic energy facilities in Hanford, Washington. Water



R. C. Y. Koh demonstrates selective withdrawal of a layer of water in a simulated reservoir. Dye makes flow pattern visible; distortion of vertical lines shows which layer of water is being drawn out of the outlet at left.

can be withdrawn selectively from a stratified reservoir almost like pulling individual sheets out of a pile of papers. Layers of water above and below the level of the outlet may hardly be disturbed; their vertical motion is inhibited by the density difference.

Selective withdrawal in the future may well become a very important tool in the management of water quality of rivers. Water with excessive dissolved salts may be released at times when it is needed only for power or navigation, but not for irrigation or municipal use. In the future, water inventories in water-scarce areas like the Pacific Southwest may well list the contents of a reservoir not only by the total volume but by subtotals according to quality.

In the Keck Laboratory, precise quantitative measurements of the flow in the withdrawal layer have been made by Dr. Robert C. Y. Koh, research fellow in engineering. In a lucite tank 15 inches deep and 8 feet long (above) he simulated a reservoir with a uniform density gradient. Thirteen layers of water of successively decreasing salt content were added very slowly in a day-long filling operation for each experiment. After another 12-hour wait, diffusion would blend the individual layers together to produce a uniform density gradient. For the experiment shown above, the density gradient was 0.03 percent per centimeter or 1.2 percent increase from top to bottom.

To make the flow pattern visible Koh dropped dye particles from the top which left vertical dye streaks as they fell. Horizontal displacement was indicated by the distortion of the dye lines, and velocities were determined by comparing photographic images taken at known time intervals.

For his doctoral thesis Koh was also successful in finding an analytical solution for the case of very low velocity, based on the viscous boundary layer equations and the diffusion equation for salt (or heat). The experiments agreed very closely with the theory for the experiments at the lowest velocities, but started to deviate, as expected, for the higher velocities.

So the question remains as to how well small scale laboratory results can be transferred to the prototype.

However, Dr. Timothy Kao, Caltech research fellow in engineering, solved the problem in his doctoral thesis at the University of Michigan in 1963, by using the Euler equations and neglecting viscous resistance and diffusion. In contrast to Koh's theory, his solution is restricted to relatively large velocities. The real reservoir case probably falls in between these two known theoretical solutions.

Work at the present time is aimed at developing some approximate theories in this in-between range, and making some experiments on a larger scale. In the meantime, various agencies are attempting to make better field measurements. The work at Caltech is supported by a three-year grant from the National Institutes of Health, U.S. Public Health Service.

These new findings will enable civil engineers, for the first time, to make approximate predictions of flow patterns for selective withdrawal, and to design into new dams appropriate outlets for management of the quality of water discharged through them.