WATER QUALITY ASPECTS OF RESERVOIR OPERATION

by

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The recent attacks on pollution and the desire for enhancement of the quality of our water resources has increased the demands on multi-purpose reservoir operation. In addition to maintaining a mass budget, we must now budget the water quality in order to satisfy the ever increasing downstream quality demands. In order to do this, we must be able to measure or predict the thermal and chemical quality of the impounded water and then be able to predict the quality of the water withdrawn from the reservoir. Careful planning, design, and operation are required in order to satisfy the multiple and often conflicting requirements.

Several techniques to improve the quality of reservoir releases have been investigated. These include selective withdrawal through an orifice or over a submerged weir, partial or complete mixing of the reservoir, injection of air and pure oxygen through penstocks, turbines, draft tubes or tailraces and controlled operation of hydraulic structures to regulate gas transfer processes. Before these techniques can be applied, we must know or be able to predict the water quality in the reservoir. This requires a knowledge of the physical processes involved in the development and decay of thermal stratification in a reservoir as well as the chemical and biological consequences of stratification. This paper will attempt to briefly describe some of these processes and consequences and to explain some of the techniques available to achieve water quality improvements in and downstream of reservoirs.

If we consider a temperate lake at the end of the winter season we have a thermal profile which consists of water very near freezing at the surface and very slightly warmer at successive depths to a maximum of 4°C, which is the temperature at which water attains its maximum density. As spring progresses the surface temperature gradually rises to 4°C and heavier water overlies colder, lighter water creating convective currents which mix the surface water with that directly below it. This process continues until the reservoir becomes isothermal at 4°C. At this point, the reservoir offers little resistance to wind induced circulation, which is generally referred to as the spring overturn.(1)

The spring overturn is characterized as a period of turbulent mixing. This results in a fairly uniform distribution of chemical constituents in the reservoir. In addition this turbulent circulation aids in the release of decomposition gases generated during the winter stagnation period and the absorption of oxygen to near its saturation level throughout the reservoir.

As the air temperature increases the water near the surface of the reservoir continues to gain heat slowly. The surface water becomes lighter than the underlying water because of the increase in surface temperature and a stable condition exists. However, the density difference created by the temperature variation is still very small and wind can still circulate the whole reservoir. This causes the heat that was added at the surface to be distributed throughout the water mass, resulting in a gradual increase in temperature of the whole water body. This process continues until the rate of heat gain is large enough to create a density differential between the surface and underlying water that will resist mixing due to wind shear. This is the termination of the spring overturn period and the temperature of the hypolimnion or bottom water is established. As additional heat is added to the reservoir, it is distributed through the epilimnion or surface mixed zone by wind generated circulation. The wind effect is now limited to this upper zone by the presence of the thermocline where the temperature changes rapidly with depth. Three regimes now exist in the reservoir: (1) the epilimnion or surface layer where temperatures are fairly uniform, (2) the thermocline which is the region of rapid temperature variation with respect to depth, and (3) the hypolimnion or bottom layer where the temperatures are again fairly uniform. This condition exists through the summer season with some variation in the thickness of the various layers due to variations in heat exchange through air-water interface, variations in inflow and outflow, etc.

The diurnal variations in heat exchange result in convective mixing in the epilimnion. This, coupled with wind shear, keeps the epilimnion temperature fairly uniform. The net heat gain during the warming season and continual mixing causes a gradual increase in the temperature and depth of the epilimnion.

The effect of wind has been discussed with regard to its influence on an isothermal water body. In addition to this, when wind causes a setup in the water surface on a reservoir, the thermocline slopes in the opposite direction to a much greater degree. The ratio of the slope of the water surface to the slope of the thermocline is on the order of $\Delta\rho/\rho$, where ρ is the density of the water in the surface layer and $\Delta\rho$ is the difference in the density of the surface water and the water below the thermocline.(2) If the thermocline is steep enough that it intersects the water surface, and the wind continues, the entire water body will mix and stratification will be destroyed.

The effect on stratification of inflow into a reservoir and changes in the outflow rate have not been studied in great detail. However, it is considered that the degree of stratification in the reservoir and the ratio of inflow or outflow to storage volume are two of the important parameters in determining this effect. The steady state selective withdrawal condition has been studied in more detail and some results will be presented in a latter section of this paper. All of these factors which affect stratification should be taken into account when predicting the temporal and spatial variations of temperature in a reservoir through a seasonal cycle.

The development of thermal stratification is accompanied by chemical and biological changes in the reservoir. The water in the epilimnion now has a reduced capacity for dissolved oxygen because of its increased temperature. During mid-summer this capacity may be one-half the capacity during the overturn period. In addition the rate of metabolic processes increases with increasing water temperature. However, the epilimnion remains essentially saturated because of the continual mixing and turbulence, which contributes more than enough oxygen to offset all of the oxygen consuming processes in this zone.

Once the thermocline forms in a reservoir the hypolimnion is essentially unaffected by wind induced circulation and light penetration and as a result is not exposed to the oxygen producing processes that exist in the epilimnion. The decomposition of organic matter, the presence of iron, respiration and other oxygen consuming processes gradually deplete the oxygen supply in the hypolimnion until only anaerobic conditions exist. The decreased supply of and increased demand for dissolved oxygen causes the summer stratification period to be the most difficult period for maintaining desirable oxygen levels downstream of an impoundment.

The decomposition of organic matter in the hypolimnion results in the production of carbon dioxide, methane, hydrogen sulfide and other decomposition gases. Excess quantities of these gases may be seen bubbling to the surface during the summer. This process not only decreases the total quantity of these gases, but also tends to distribute them throughout the depth of the reservoir.

The suspended materials in the epilimnion during summer stratification consists primarily of plankton with increasing concentrations of organic and inorganic material with depth to a fairly uniform concentration in the hypolimnion. Dissolved solids are slightly more abundant in the thermocline and hypolimnion than in the epilimnion. After the oxygen has been depleted from the hypolimnion and acid forming substances have built up the hydrogen ion profile consists of a fairly uniform concentration in the epilimnion and then an increase with depth with a larger gradient through the thermocline than in the hypolimnion.

The decay of summer stratification begins when the fall air temperatures begin to cool the surface water and cause it to sink and mix with the underlying water. This process will continue throughout the fall until the reservoir becomes isothermal once again at 4^{o}C. The reservoir is now susceptible to wind induced circulation and the fall overturn begins. As the air temperature continues to decline, the water surface becomes colder and lighter than the water below, which creates a stable condition. This condition will remain until spring if ice covers the lake. In areas where the surface does not freeze, circulation may continue through the winter.

There are several techniques available for controlling and enhancing the quality of reservoir releases. The principle of selectively withdrawing water from various levels in a reservoir was probably first suggested by Hugh S. Bell(3) in 1942. Several analytical and experimental investigations have been conducted since the inception of this idea; however, very little practical design guidance has evolved. A study was initiated in 1966 at the U. S. Army Engineer Waterways Experiment Station (WES) for the purpose of developing generalized guidance for determining the vertical limits of withdrawal and the velocity distribution therein for flows from a randomly density stratified impoundment through a submerged orifice.(4) The experimental facility is shown in Fig. 1. Flow patterns were observed in the one-foot-wide transparent channel by dropping dye particles into the flow. The deflection of the dye streak allowed the determination of the withdrawal zone limits and calculation of actual velocities within the zone. The discharge through the intake and the density profile in the flume were measured to complete the basic data. A definition sketch is shown in Fig. 2.

The data analysis resulted in a generalized relationship between discharge, intake elevation and the density profile (Fig. 3), which can be used to predict the upper and lower limit of the withdrawal zone. A normalized relationship between velocities, elevation, and density differences was also developed (Fig. 4) and this allows calculation of the actual velocity profile within the withdrawal limits, regardless of the shape of the density profile. With this information known, the contribution of any water quality parameter from any elevation can be determined. Integration over the withdrawal zone then gives the value of that particular water quality parameter entering the intake. The most extensive evaluation of the WES selective withdrawal technique has been conducted by H. M. Clay, Jr., and E. G. Fruh.(5, 6)

Another effective means of selectively withdrawing water from a reservoir is by using a submerged weir. This technique may be especially beneficial at projects supplying hydroelectric power because of the relatively large water requirements. An investigation, similar to that conducted for the submerged orifice, was conducted at WES for flow over a submerged orifice from a randomly density stratified impoundment. The experimental facility is shown in Fig. 1 with a weir in place of the orifice and Fig. 5 is a sketch defining terms. A generalized relationship between discharge, density, and the withdrawal zone thickness is shown in Fig. 6. The normalized velocity distributions and other details of the investigation are contained in a WES technical report.(7)

Another possible technique for improving water quality is by artifically inducing circulation in the reservoir in order to partially or completely eliminate density stratification. This is referred to as destratification and can be accomplished by various pneumatic, hydraulic, or mechanical methods. The primary advantage of destratification is that it increases the dissolved oxygen content of the hypolimnial water. If anaerobic conditions exist in the hypolimnion iron, manganese and other chemical constituents may appear in solution. This results in taste and odor problems and the need for increased treatment before this water can be used for water supply. Anaerobic decomposition gases are also produced under these conditions. Artificial mixing exposes the hypolimnial water to the oxygen absorption processes resulting in increased quantities of dissolved oxygen in these waters.

Several prototype destratification attempts have been made and these have had varying degrees of success. One of the largest destratification attempts within the Corps of Engineers was made at Allatoona Reservoir in northwest Georgia.(8) Allatoona Reservoir has a surface area of 11,860 acres and contains 300,000 acre-feet of water during the summer behind a 190-feet-high dam. The epilimnion reaches a depth of approximately 50 feet by mid-September. An air diffuser system was selected to induce circulation primarily because of the systems flexibility. An air flow rate of 1200 cfm at 75-100 psi was the calculated rate required to destratify Allatoona based on a stability analysis with an efficiency of energy transfer in an air diffuser system of one percent based on previous studies.

Undoubtedly some water quality improvements were realized from this study. However, it is questionable whether this technique can be used efficiently on a large impoundment without improvements in the technique. In addition, destratification removes the possibility of providing waters of different quality downstream through selective withdrawal devices. Depending upon the downstream objectives, this selectivity may be absolutely essential. It appears that the most beneficial application of destratification, pending further research, is in small water supply impoundments where selectivity is not required.

The last water quality improvement technique to be discussed is reaeration of impoundment releases. Several studies have been conducted concerning means of aerating stream flows with mechanical mixers or air diffusers; however, this discussion will concentrate on controlled design and operation of hydraulic structures to regulate gas transfer processes and air injection into penstocks and turbines.

The increased demand for waste assimilation in the great majority of rivers and streams in the United States has resulted in dissolved oxygen concentrations that are less than adequate. The release of hypolimnial water from reservoirs also contributes to the problem of inadequate oxygen supplies. A solution to this problem is to aerate the flows as they are released from an impoundment. Normally a structure is designed to release a desired flow and to dissipate the energy with as little turbulence as possible in order to minimize the protection required in the downstream channel. Although some oxygen absorption does occur in this process, it may not be adequate to meet the downstream demand. It may be desirable to provide an adequate amount of downstream protection so that the turbulence, and consequently oxygen absorption, may be increased in the energy dissipator by controlled gate operation. A recent dissertation by A. G. Holler, Jr. (9) included both model and prototype observations of the Meldahl Locks and Dam on the Ohio River and the results indicate that substantial increases of dissolved oxygen can be attained through slight structural and operational modifications.

A recent attempt was made to aerate flows from Table Rock Lake in southern Missouri by air injection through the penstock and turbine and by in-lake air diffusion by the Little Rock District of the Corps of Engineers. Lake Taneycomo, directly downstream of Table Rock Lake, contains a trout hatchery and requires cold water releases from Table Rock. This necessitates withdrawal from the hypolimnion, which has inadequate concentrations of dissolved oxygen. The primary objective of this test program was to develop relationships between oxygen absorption, air to water quantity ratios, turbine discharge, and the location of injection.

The in-lake air diffuser system consisted of two diffuser arrays located in the vicinity of the penstocks. The objectives of these tests were to determine the effectiveness of this type of air injection system in increasing the dissolved oxygen content of the power releases, evaluate the effect of elevation and location of the diffusers on oxygen absorption and to regulate the dissolved oxygen concentration of water entering the penstock for further air injection tests. The results of the tests at Table Rock Lake are currently being evaluated and will be presented in a future report.

In contrast to the desire to aerate reservoir releases is a problem existing on the Columbia and Snake river system in the Pacific Northwest concerning nitrogen supersaturation.(10) This problem is attributed, at least in part, to the construction of dams in this system, which has eliminated the turbulent reaches in the rivers. This turbulence is a natural means of releasing gases from supersaturated water.

The head waters of the Columbia and Snake rivers are slightly supersaturated with nitrogen before they pass through any impoundments. As the water passes over the spillways along the rivers, it is subjected to high pressures at the toe of the spillway and in the stilling basins resulting in absorption of entrained air to supersaturated levels. The reaches between the exit channel at one structure and the pool of the downstream structure are not long enough to purge the supersaturated gases from the water. The nitrogen, being a fairly inert gas in solution, remains while the oxygen may be consumed by various oxygen consuming processes. Fish exposed to this nitrogen supersaturated water contract the gas embolism disease, which is similar to the "bends" in a diver, and dye if exposure continues.

This high degree of supersaturation occurs only where flows are passed over the spillways. Several solutions are being investigated by the Corps of Engineers. These include "flip lips" on the spillway to prevent the spillway flow from diving deep into the tailwater and passing flows through skeleton bays where turbines have not yet been installed. There are also several research projects being sponsored by the Corps in an effort to understand and alleviate the problem

This paper has attempted to briefly explain some of the water quality considerations that must be taken into account in the planning, design, and operation of a water resource project. A complete understanding of the downstream objectives must be obtained before a project can be designed and operated properly. These objectives and economic considerations will form the basis for deciding which type of water quality control technique will be required for a specific project. This decision depends upon the temporal and spatial variations of temperature and chemical constituents within the impounded water. Several techniques based on a heat budget analysis are available for predicting the temperature variations in a reservoir. These techniques rely on various simplified assumptions and coefficients which require prototype data to evaluate. The state-of-the-art regarding the prediction of chemical constituents in reservoirs is even less advanced. Much more research is required in order to obtain a better understanding of the physical, chemical, and biological processes involved in flow into, through, and from a reservoir.

The opinions expressed in this paper are those of the author and do not necessarily reflect the opinion of the Corps of Engineers.

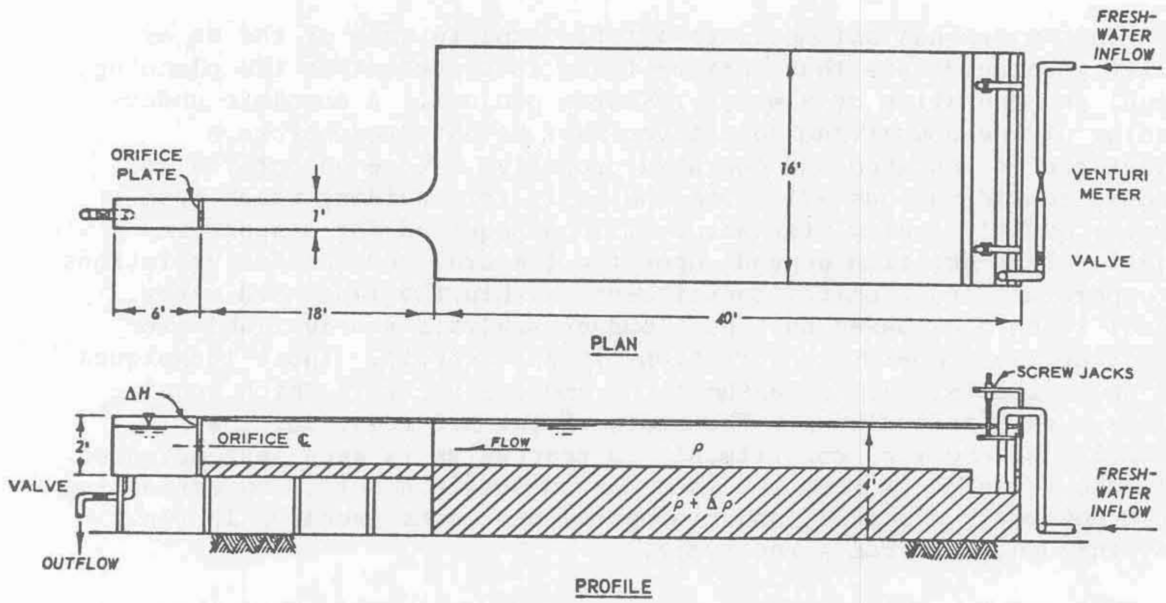


Fig. 1. Experimental facilities

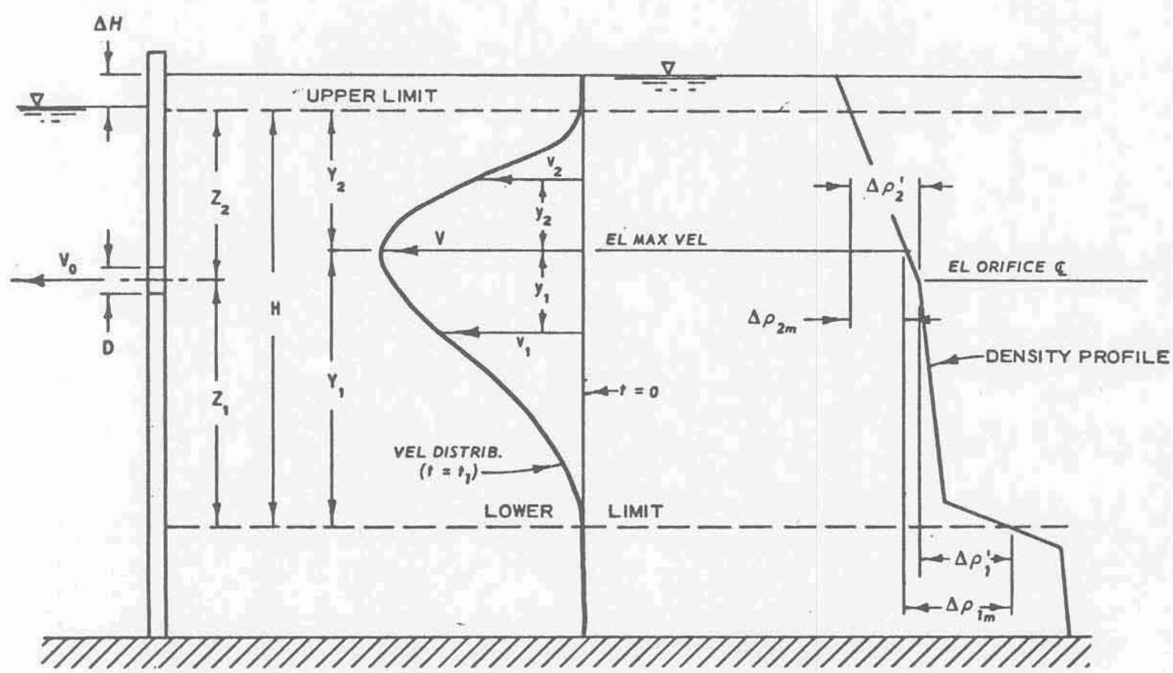


Fig. 2. Definition sketch for flow through orifice

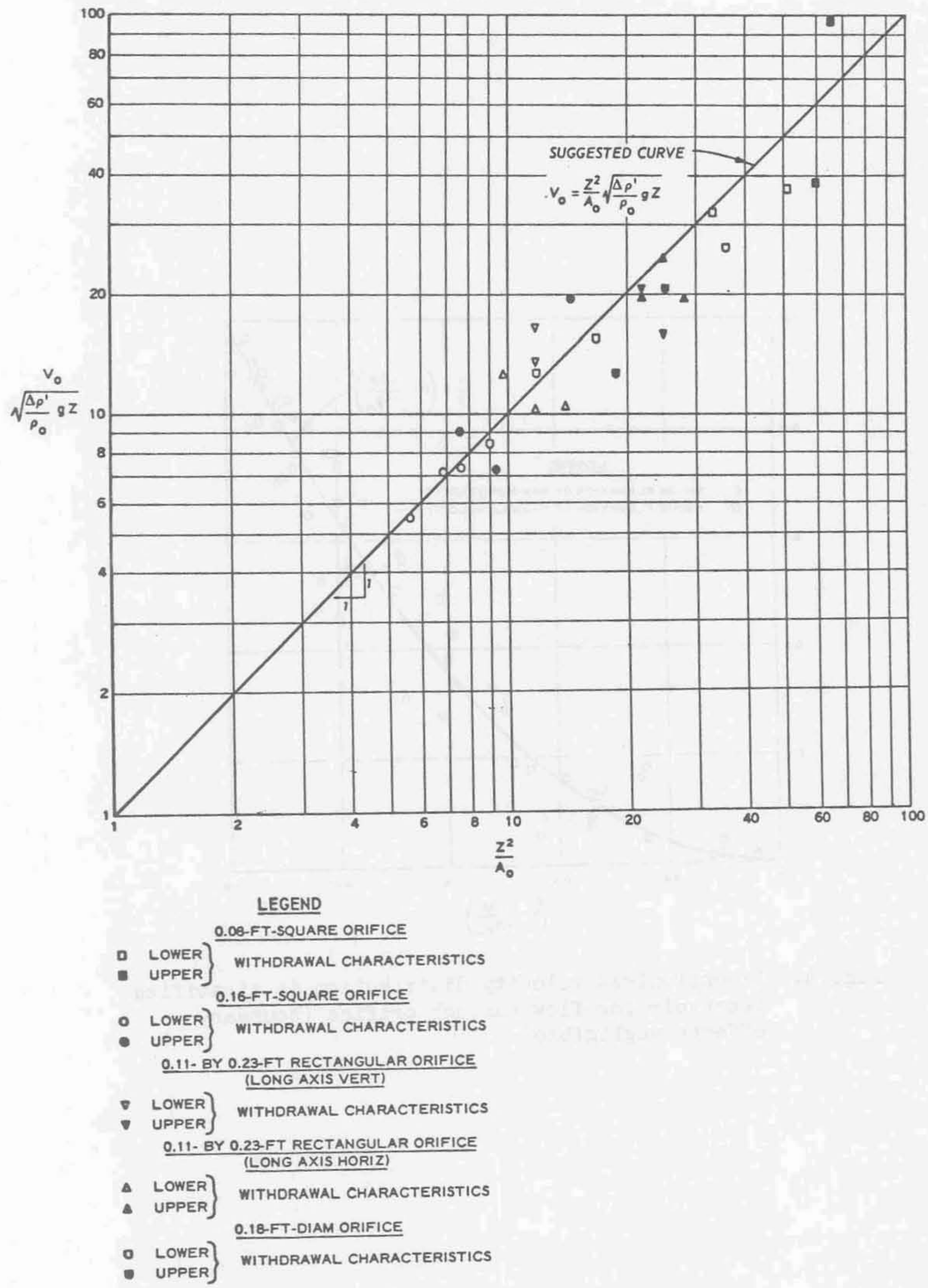


Fig. 3. Withdrawal characteristics of orifices

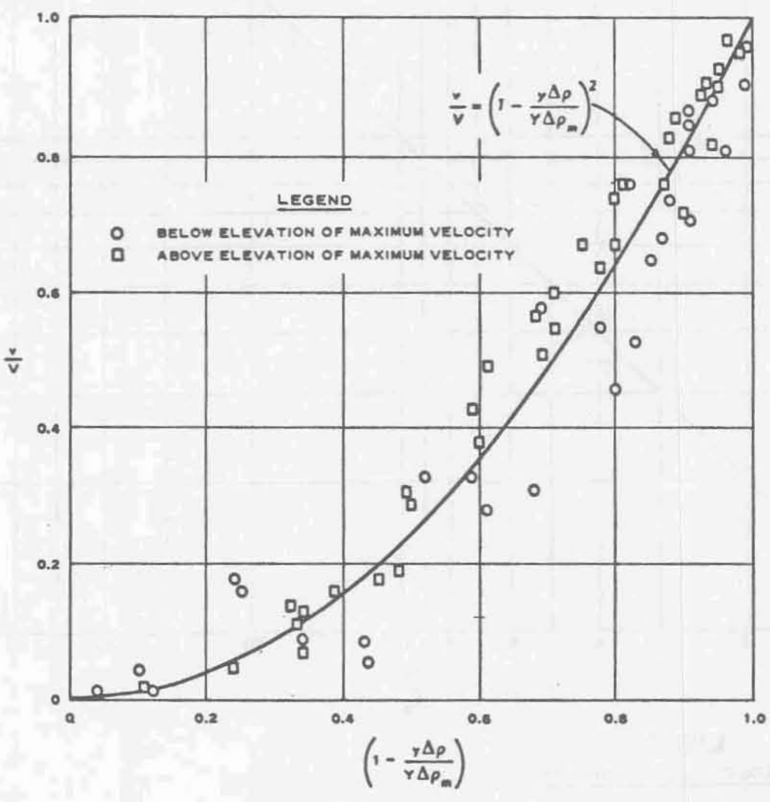
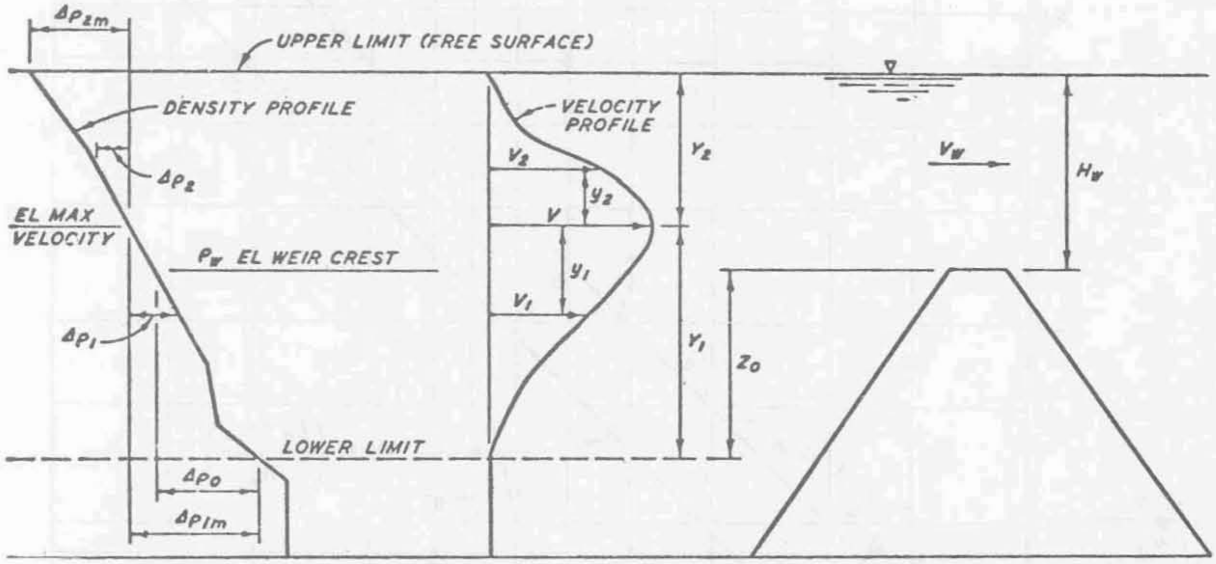
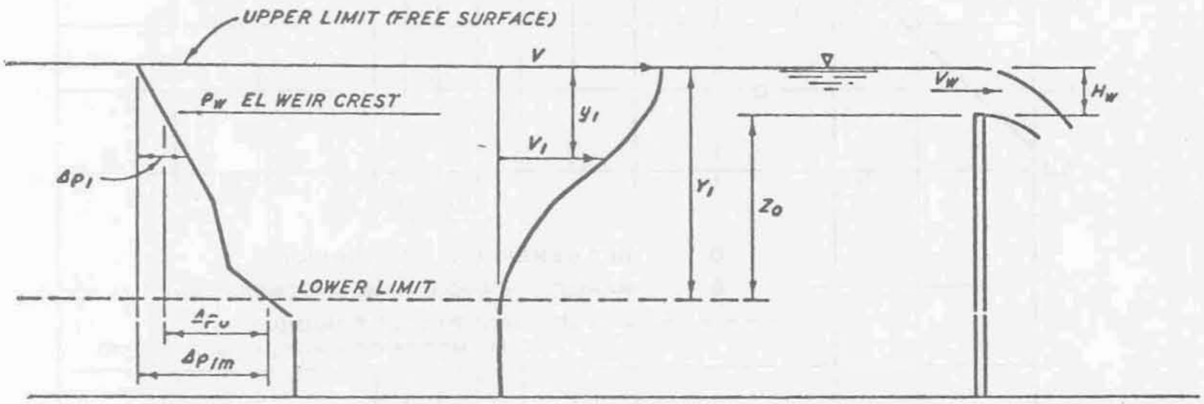


Fig. 4. Dimensionless velocity distribution in stratified reservoir for flow through orifice (boundary effects negligible)



a. Submerged weir flow



b. Free weir flow

Fig. 5. Definition sketch for flow over weir

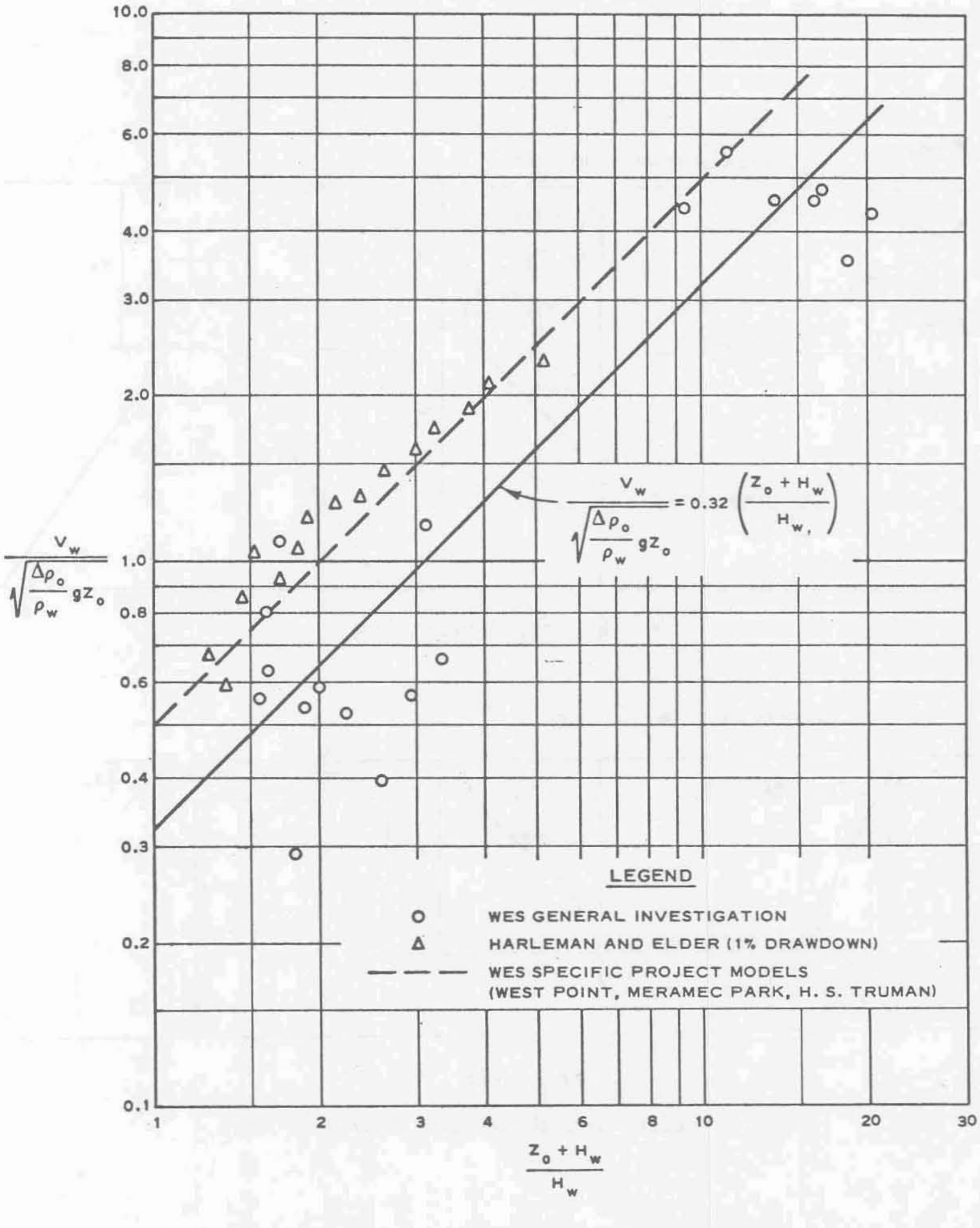


Fig. 6. Withdrawal characteristics of weirs

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