PRELIMINARY STUDY ON THE PREDICTED WATER CHANGES OF THE LOWER SNAKE RIVER DUE TO THE EFFECTS OF PROJECTED DAMS AND RESERVOIRS

PART I: FORECASTING WATER TEMPERATURE CHANGES DUE TO FLOW THROUGH INTERMEDIATE DEPTH RESERVOIRS

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Prepared for: Bureau of Commercial Fisheries
Fish Passage Research Program
Bldg. 67, U.S. Naval Air Station
Seattle 15, Washington

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Material Requested: 1. Preliminary Study on Predicted Water Quality Changes of the Snake River. Study to include an estimate of the possible effects of the following list of dams and also an evaluation of the potential for control of river temperatures and oxygen levels in the Snake River: Ice Harbor, Lower Monumental, Lower Granite, Asotin, China Gardens, High Mountain Sheep, Hells Canyon, Oxbow, Brownlee, Penny Cliffs, and Bruce's Eddy. The preliminary study will include a review of data required for such a study, the data presently available, an estimate of the time required to develop the information, and an estimate of cost.

Prepared by Wayne V. Burt with the assistance of W. Bruce McAllister.

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November 12, 1963

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ABSTRACT AND CONCLUSIONS

A method has been developed for forecasting temperature changes for cold water passing through intermediate depth reservoirs during summer and fall. Preliminary studies indicate that some benefits, in the form of lower downstream water temperatures, may be expected during critical times of the year, after all six projected medium depth reservoirs are in operation on the lower Snake River, provided that low temperature water is available from upstream.

The results of these studies indicate that water passing through the six reservoirs may be exposed to the atmosphere in a turbulent condition during at least 25% of the time of passage before it leaves the surface to flow as a density current toward the reservoir outlets. For this reason oxygen depletion should not be as serious a problem in the density currents passing through the reservoirs as it is in the subsurface waters of deep reservoirs such as Brownlee.

Previous temperature forecasts have been made for tailrace discharge temperatures for the projected High Mountain Sheep and Nez Perce reservoirs. These forecasts indicate that any combination of dams and associated reservoirs on the Snake River at its confluence with the Salmon River will deliver cooler than normal water into the projected China Gardens reservoir. China Garden is the first of the six medium depth reservoirs on the lower Snake River. Similar water temperature forecasts have been made in the past for the projected

Bruce's Eddy reservoir and the Clearwater River between Bruce's Eddy and Lewiston. These forecasts indicate that both the Bruce's Eddy and Penny Cliffs Reservoirs will lower the temperature of the Clearwater River as it flows into the projected Lower Granite Reservoir above Lewiston, Idaho. The beneficial effects of both reservoirs will increase with increasing discharge rates.

Past studies by the author on several deep reservoirs have all indicated that downstream temperatures may be lowered during critical times of the year by manipulation of discharge from outlets at several depths. Cold water may be conserved when it is not needed and then discharged when it is needed.

INTRODUCTION

The whole crux of studying the effects of the six medium depth lower Snake River reservoirs on temperature conditions in the river depends on the ability to forecast temperature changes within each individual reservoir.

The methods for forecasting temperature changes in reservoirs have been developed over the past decade. Raphael (1962) has developed a system of forecasting temperature changes in shallow reservoirs on the Columbia River. The shallow depths, small volumes and high discharge rates insure vertical mixing and turbulence from top to bottom over most of the year. On the other extreme, the author and others have developed and used several systems for forecasting temperature changes in deep reservoirs where layered or nearly layered flow occurs whenever a vertical density gradient exists.

Unfortunately, the six lower Snake River reservoirs are medium depth, medium discharge reservoirs and neither of the above systems may be used except for times when the vertical density gradient is very slight (or absent) or the rate of discharge is at an absolute abnormal minimum.

Up to the present time no one had been able to handle the problem due to lack of knowledge of flow and mixing patterns in medium depth reservoirs. Turbulent mixing and flow takes place in the upper end of these reservoirs. Some sort of layered flow takes place in the deeper lower end of these reservoirs whenever a vertical density gradient exists.

Recent work by Yih (1958), Duncan et al. (1962), Harleman (1961), Debler (1959) and others has furnished the theory and a beginning of the empirical verification of the theory for forecasting flow conditions in all reservoirs. Specifically, they show that a fundamental relationship should exist between the flow pattern within the reservoir and the vertical density gradient, the discharge and shape parameters of the reservoir. This heretofore missing relationship allows us to develop a system for forecasting temperature changes within the six medium depth reservoirs of interest. A discussion of the above series of studies on flow in channels and reservoirs appears in the Appendix. It should be emphasized that more field measurements in actual reservoirs are required before these relationships will be completely understood.

FLOW PATTERN IN INTERMEDIATE RESERVOIRS

For convenience we will define intermediate reservoirs as those similar to the six reservoirs on the lower Snake River beginning with Ice Harbor and running upstream to China Gardens. Figure I is a schematic drawing of the current structure in an intermediate reservoir during the late spring, summer, and early fall. This type of current structure should occur whenever there is a measurable vertical temperature change and the discharge rate is not at a maximum. The reservoir is divided into five zones for purposes of discussion.

Zone I

Zone I consists of the turbulent area at the up river end or head of the reservoir between the points A and B on Figure I. Water enters the reservoir from the river or next reservoir above at point A. The temperature of the inflowing water is determined by conditions upstream. Flow is relatively rapid and turbulent between points A and B. The flowing water is warmed or cooled from the surface depending upon its temperature and the surface heat budget at any given time. The heat budget is a function of meteorological conditions in the air over the reservoir. The exact distance from A to B (the length of Zone I) is constantly changing from hour to hour and day to day. The position of B depends on discharge, changes in discharge, changes in the rate of heating or cooling at the surface and changes in the water level in the

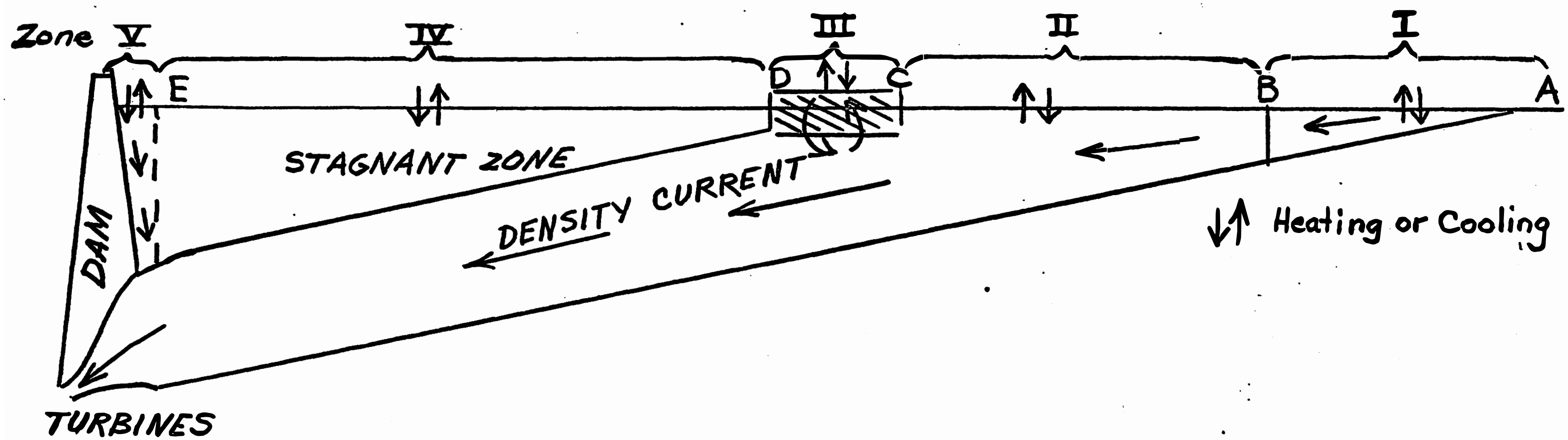

Figure 1. Schematic diagram of processes taking place in intermediate stratified reservoirs due to the combined effects of surface heating and cold water inflow.

reservoir. At point B the reservoir has widened sufficiently so that current will slow down and the turbulence will be reduced. Heating will not penetrate all the way to the bottom downstream from point B.

If the water in Zone I is low in oxygen content there will be a rapid movement of oxygen from the atmosphere through the surface into the water.

Zone II

Heating or cooling may be taking place in Zone II depending on the water surface temperature and the heat budget. If surface heating is taking place, a vertical temperature gradient will develop* as the water passes from B to C. If cooling is taking place over Zone II, the cooled surface waters will sink, causing some overturn and turbulence will increase. If cooling is sufficient to overcome vertical thermal gradients set up by previous heating, the overturn and increased turbulence will extend to the bottom. Whenever this occurs, Zones I and II will merge and the point B will move downstream to point C.

At point C the downstream current leaves the surface and dives under the surface layer as it flows as a sub-surface current toward the turbine outlets. After the current leaves the surface, we will call it a density current.

The discharge temperature from the reservoir is largely determined by inflowing water temperature and the heating or cooling that

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* The term temperature gradient is used to mean any temperature decrease with depth.

takes place at the surface in Zones I and II. After the water leaves Zone II some heating will take place as warmer water is entrained from above at the shear zone just above the density current. Some warmer water will also be entrained from above due to turbulence right at the face of the dam. If the water in Zone II is low in oxygen content, oxygen will move down from the atmosphere through the surface into the water.

Zone III

Zone III is a transition zone or boundary zone between the new water flowing in from upstream and older water which has been in the reservoir for some time. The new and old refer to length of residence in the reservoir. Continuous boundary changes will take place between the points C and D. Wind mixing, cooling from above, and inertia related to changes in discharge will all effect the position and extent of the zone. Increase in discharge will move the zone downstream. Decreases in discharge will move it upstream.

Zone IV

The stagnant zone between the points D and E (above the density current) contains water that is not participating in the major current pattern in the reservoir. The top layer in this zone will be relatively stagnant when compared to the density current. Wind stress on the surface will bring about some mixing and will cause currents in the surface layer of zone IV.

The temperature of the very surface layer of zone IV will be changing continually with day to day and hour to hour changes in the local weather over the reservoir.

Orographic conditions will bring about some mixing from below which may extend all the way from the density current, through the stagnant layer, to the surface. Sharp bends in the old river channel, the sides of islands or channel restrictions will all cause local turbulence with some vertical mixing between layers.

Zone V

The boundary zone right next to the dam will have some turbulence within it due to a variety of causes. Any vertical turbulence will cause some mixing between the two layers. Causes of turbulence may be inertial, related to discharge changes, or due to vorticity in the density current as it increases in velocity or entering the turbine intakes.

From a study of Figure I it is obvious that a large number of different factors are affecting the temperature and current structure in intermediate size reservoirs such as those on the lower Snake River. For exact forecasting we need a large number of current measurements over a variety of conditions to describe the expected current structure within intermediate reservoirs. In the meantime, the relationships discussed in the Appendix give us some quantitative idea of what to expect in the lower Snake River reservoirs. A forecasting system can be developed to show the general trends of what to expect in these reservoirs and then be corrected as more qualitative information on flow relationships becomes available.

It should be mentioned that both Army Engineer personnel and people employed by the Bureau of Commercial Fisheries have measured small vertical temperature gradients in the Ice Harbor reservoir during summer. Due to long exposure both the water coming downstream into the reservoir and resident water in the reservoir are either in equilibrium or very near in equilibrium with the atmosphere most of the time. Both river surface and reservoir surface are influenced by the same climatic conditions. Thus, one would not expect strong thermal gradients. The very fact that they are measured indicates that the reservoir would stratify to some extent if cold water were available at its upstream end.

FORECAST

All six of the intermediate reservoir systems that are or will be formed by dams on the lower Snake River have somewhat the same characteristics as to depth, volume, and area. The upper two will have less discharge than the lower four due to the inflow from the Clearwater River. The most important related factor is depth which enters as a square in the computation of the Froude number (see Appendix). Conditions are similar enough that a forecast for one reservoir will tell us what to expect from the other five. Such a forecast may be used to see if it may be worthwhile to make detailed forecasts for all six reservoirs.

The Army Engineers (Walla Walla District) do not have complete area, volume, elevation, and dam characteristics for any one of the reservoirs. The most data are available for Ice Harbor and Lower Granite. Ice Harbor was chosen because its depth, volume, and surface area are about the average for the depths, volumes, and surface areas of all six reservoirs. Missing area, volume, elevation data for Ice Harbor were inferred from available data for Lower Granite. Differences between the shape of the two reservoirs would not materially effect the conclusions reached.

Question to be answered:

If all six reservoirs were in operation and cold water were available from discharge into the upper reservoir, would any trace of the cold water be left by the time it was discharged through the last dam downstream? Another way of stating the question is: Would the cold water coming into the upper reservoir be heated up to equilibrium with the atmosphere by the time it left the last of the six reservoirs?

Let us assume that all six dam and reservoir systems have the same shape and other charactersitics as Ice Harbor. Let us further assume that the relationships between the thickness of the density current, discharge rate, and vertical gradients are the same for all six reservoirs. A last assumption is that the results of Debler's (see Appendix) model study apply to full scale reservoirs of the same conformation.

The above assumptions then allow us to forecast the temperature rise for cold water passing through 1, 2, 3, 4, 5, or 6 reservoirs with any given initial inflowing water temperature.

The exact numerical step by step process of the forecasting will not be discussed. It is similar to other forecasts by the author. The thickness of the density current was derived from Figure 2 which in turn was derived from the shape of the Ice Harbor reservoir, using Debler's (see Appendix) relationships. The area and volumes of zones I and II (Figure 1)were derivedfrom the shape of the reservoir and the thickness of the density current.

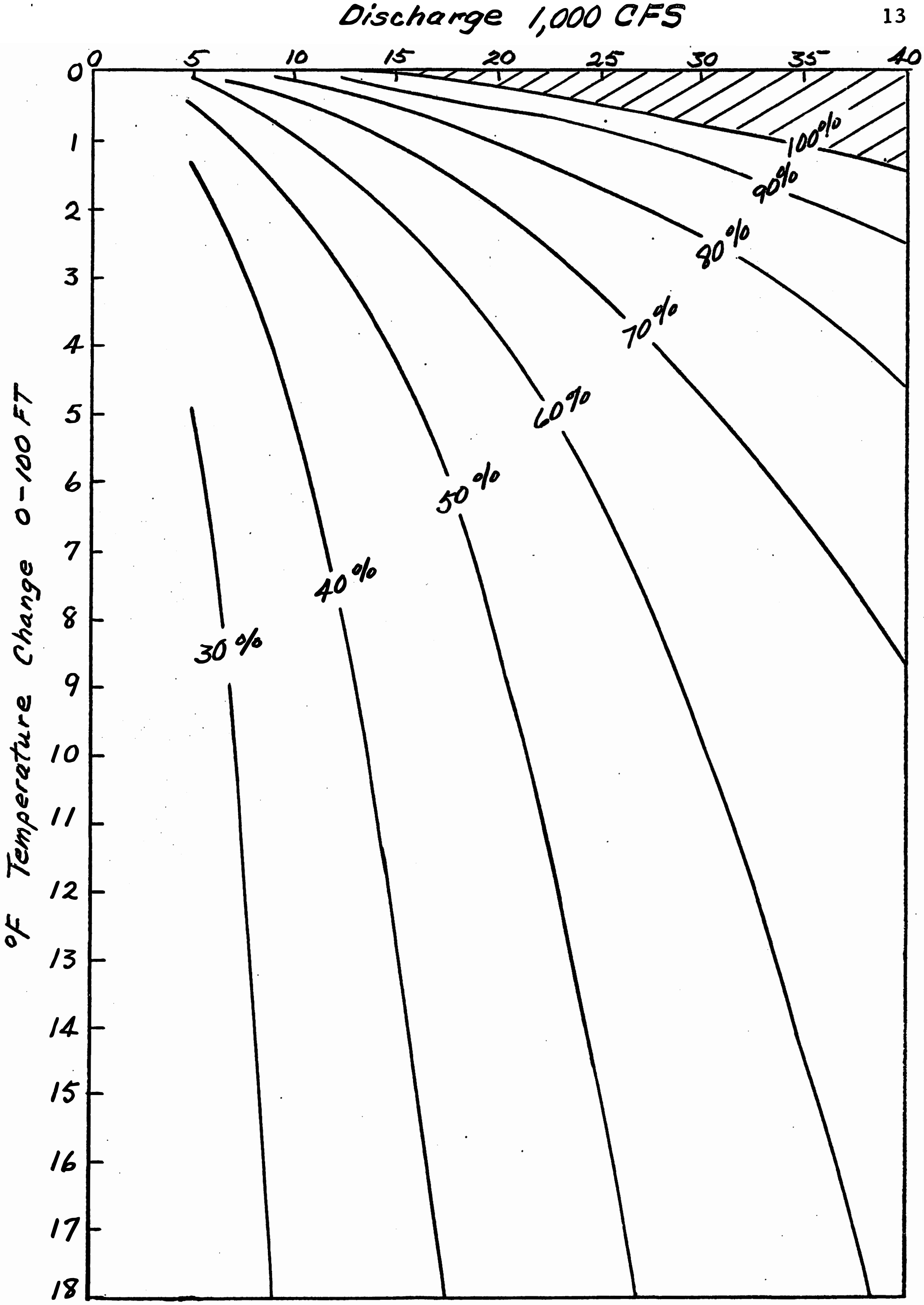


Figure 2. Thickness of density currents in stratified intermediate reservoirs as a percentage of the maximum depth of the reservoir.

The travel times from A to C (Figure 1) were derived from the shape of the reservoir and the discharge rate. The rate of heat flow across the surface of zones I and II was then computed from the surface temperature of the water and the heat budget for the area. Later revisions of heat budget graphs for the Lewiston area appearing in Burt (1958) were used for this calculation.

July 15 was selected for the forecast because it is near the time of maximum heating over cold water surfaces in this area. The water surface temperature in zone IV of the reservoir was assumed to be 72° from past surface temperature data for Ice Harbor. Three different water temperatures were selected for the water entering the reservoir from above: 67° F. $\Delta T = 5°$; 62°, $\Delta T = 10°$, and 52°, $\Delta T = 20°$.

In each situation the water was allowed to pass through one reservoir with the characteristics of Ice Harbor. The amount of heating was calculated and applied to the discharge water. The water was then assumed to enter the next reservoir (again with the characterisitcs of Ice Harbor) and the amount of heating calculated on the basis of the new discharge temperature. The calculations were then repeated for the 3rd, 4th, 5th, and 6th reservoir.

In all, seventy-two forecasts were made for the six reservoirs, the three original inlet temperatures and four different discharge rates (10, 000-20, 000-30, 000 and 40, 000 CFS). The 1925-1958 average July discharge (with 1985 depletions) is 34, 000 CFS. The minimum monthly mean July discharge for the same period was 13, 000 CFS.

CAUTIONS

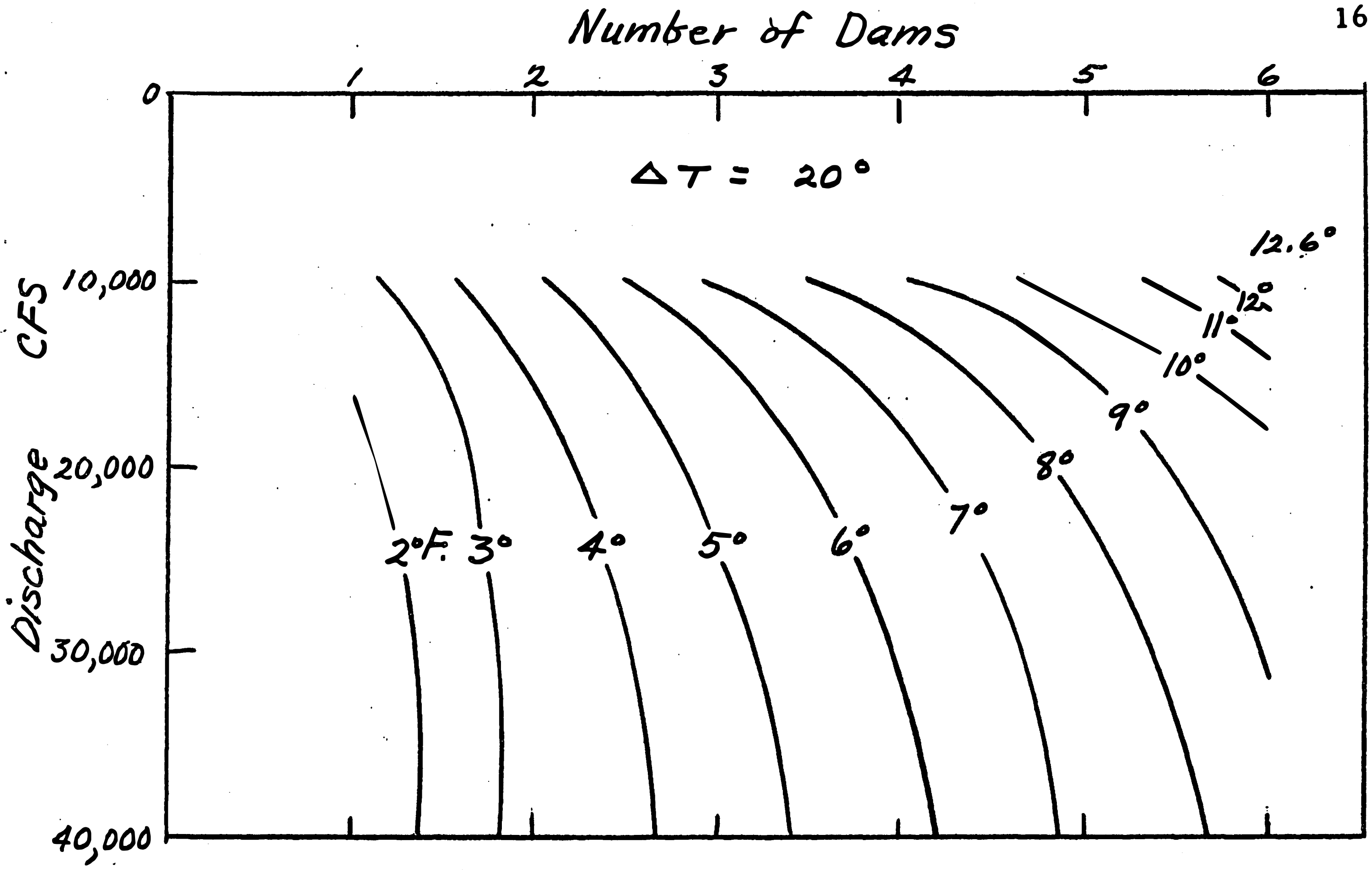
The forecasting has been simplified for this report by not considering the effect of the heating taking place in any individual reservoir on the thickness of the density current. If further forecasts are made, a refinement will be added to take this effect into account. For this reason these forecasts should be considered as examples of what can be done in the way of forecasting rather than true forecasts of what will occur.

The accuracy of any forecast for reservoirs of the type under consideration will depend upon the applicability of the relationship developed by Debler (see Appendix). For this reason an effort should be made to locate reservoirs with similar characteristics to those under consideration and make actual current measurements within this reservoir. The reservoirs examined must have vertical temperature gradients to furnish useful data.

RESULTS OF FORECASTS

The results of forecasts are shown on Figures 3 and 4.

The vertical scale is discharge in cubic feet per second. The horizontal scale is the number of dams traversed. The curved lines show the number of degrees rise in temperature which should occur for any given number of dams. The top part of Figure 3 is for a temperature rise of 20° between the temperature of water flowing in at the



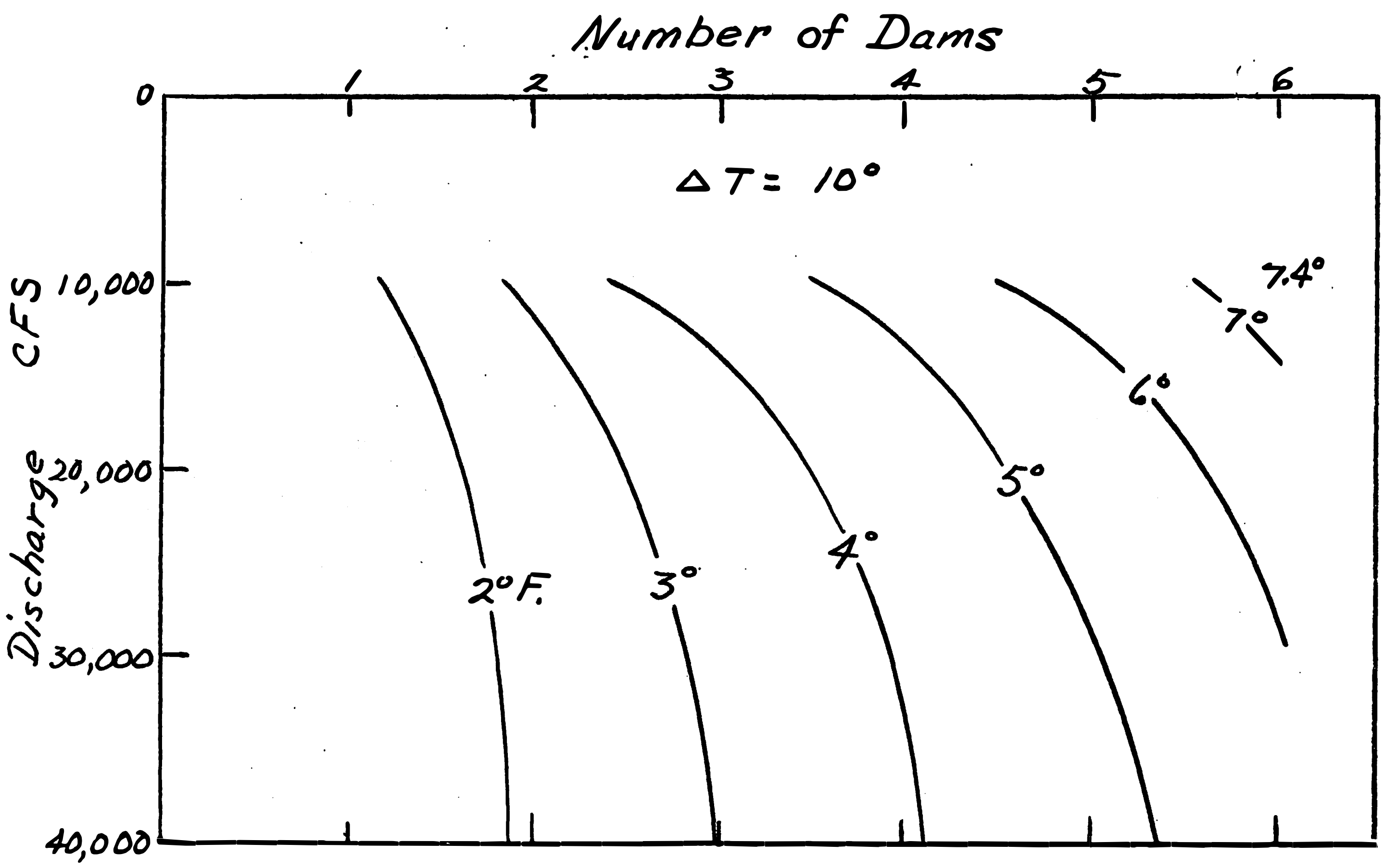


Figure 3. Temperature rise in degrees F. in water flowing through intermediate reservoirs with the characteristics of Ice Harbor reservoir. ΔT is the vertical temperature change per 100 feet just above the dam.

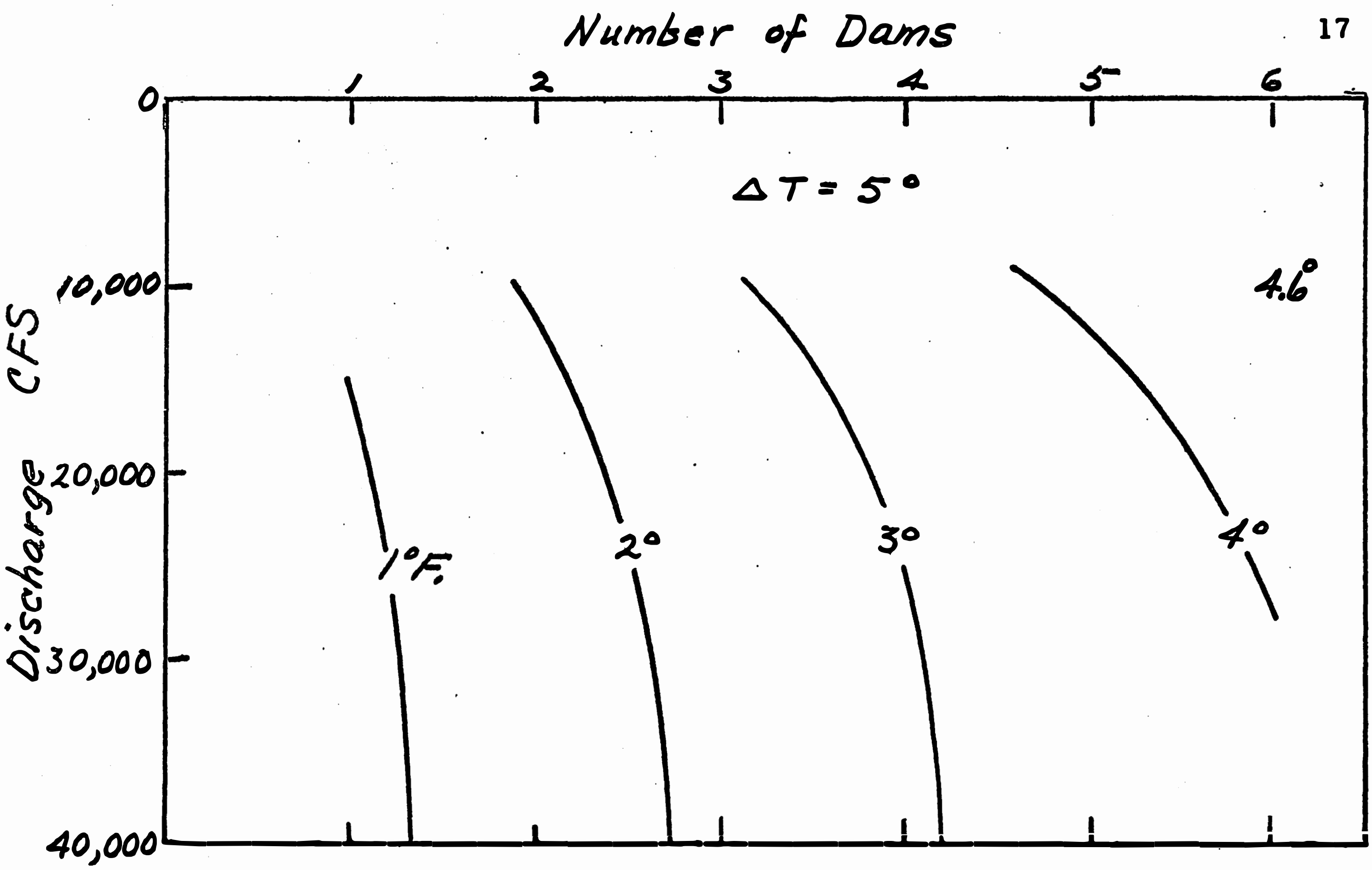


Figure 4. Temperature rise in degrees F. in water flowing through intermediate reservoirs with the characteristics of Ice Harbor reservoir.

upper end of the reservoir and the surface temperature of the water in the stagnant area near the lower end of each reservoir. The lower part of Figure 3 is for a ΔT of 10° and Figure 4 is for a ΔT of 5° F.

Example: What is the discharge temperature of the last dam if T = 10 and the discharge equals 30,000 CFSΣ. From the lower half of Figure 3 enter the diagram with 30,000 CFS and 6 dams and find the curve labeled 6° F. The surface temperature is 72° F. Ten from seventy-two is equal to the inflowing temperature of 62° F. Sixty-two plus a 6° rise in temperature equals 68° F., the discharge temperature.

FUTURE FORECASTS

If more detailed forecasts are made for the six intermediate reservoirs on the lower Snake River, the shape characteristics for each individual reservoir should be used.

The Walla Walla District of the U.S. Army Corps of Engineers has the basic data available for computing all the necessary parameters.

The following data are needed for more detailed temperature forecasts:

1. Area and volume versus elevation curves for the whole depth range of each reservoir.
2. Topographic maps for the area of each reservoir.
3. Surface area and total volume for segments of the reservoir. If these data are readily available for segments between each

river mile, such data would be ideal. A substitute would be the width and vertical cross sectional area at each river mile.

4. Expected daily and hourly discharge for different mean monthly discharge rates for each reservoir. Will one turbine run part of each day and several turbines for the rest of the day? Will discharge rates change over the weekend?
5. Transverse cross sections through the projected China Gardens and Asotin Dams.

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APPENDIX

Duncan, Harleman and Elder (1962) and Harleman (1961) made a study of withdrawal of water from vertically stratified reservoirs using temperature data from Fontana and other TVA reservoirs. They inferred the vertical thickness, b, of the internal density current flowing into the turbine intakes from a critical examination of the shape of the vertical temperature (density) depth curve at any given time.

The end product of the Fontana study is an empirical relationship between the ratio b/Z_o and the densiometric Froude number F_i, where Z_o is the vertical distance from the reservoir water surface to the vertical centerline or midpoint of the turbine intakes.

The densiometric Froude number, F_i, is

$$F_i = \frac{Q}{W Z_o^2} \sqrt{\frac{\rho}{g\beta}}$$

The densiometric Froude number is non-dimensional, hence any consistent system of dimensional units may be used.

Q = Turbine discharge

W = width of the reservoir where temperature observations are made and at the depth Z_o

Z_o = depth from the surface to the centerline of the turbine intakes

ρ = density of the water at Z_o

g = acceleration due to gravity

β = vertical density gradient at the depth Z_o

Yih (1958) had shown that a relationship should exist between the flow pattern and F_i for high Froude numbers. He and Harleman (personal communication) stated that there is a critical value of the Froude numbers of $1/\pi$ (0.318) for the stratified flow in a channel. For Froude numbers above $1/\pi$, water is drawn from all layers up to the surface and selective withdrawal cannot occur. Yih's (1958) theoretical study indicates that for Froude numbers below the critical value of $1/\pi$ stratification will occur in the channel and an internal density current will be set up and the flow out of the end of the channel will not extend all the way to the surface.

Yih's criterion was applied to the range of parameters expected in the lower Snake River reservoirs. This study showed that whenever there is no vertical temperature gradient, the flow will take place all the way to the surface (this is well known from other considerations). Flow may extend all the way to the surface with small density gradients, provided the discharge is great enough. For example, $F_i = 1/\pi$ when the temperature changes one degree per 100 feet (69°F. to 70°F.) and Q = 40,000 CFS for a reservoir with the average dimensions of the lower Snake River reservoirs. Thus, one would expect flow all the way to surface whenever the temperature gradient was approaching zero or whenever the discharge was well above average with a very slight temperature gradient.

Two problems arise in using the results of Duncan et al. (1962) and Harleman (1961) to predict what to expect in the low reservoirs on the lower Snake River.

Duncan et al's.(1962) data for TVA reservoirs covers a very restricted range in F_i from $F_i = 0.0035$ to $F_i = 0.016$. Their data is sufficient to show that the ratio of b/Z_o is greater than 0.5 for values of F_i greater than 0.016. This means that for reservoirs where the flow may be above or well below the centerline of the turbine intake, the thickness of the layer flowing into the turbine intake is numerically greater than half the vertical distance from the surface to the centerline of the turbine intakes whenever $F_i > 0.016$.

The TVA reservoirs are quite different from the lower Snake River reservoirs. Fontana and the other TVA reservoirs have outlets well above the bottom, permitting flow from well below the depth Z_o while most, if not all, of the Snake River reservoirs have or will have turbine intakes at the bottom of the reservoir. For this reason, you would expect a different numerical relationship between b/Z_o and F_i for the lower Snake River reservoirs. The principal use we can make of the TVA study is to help us realize that a relationship of this type should exist for intermediate depth reservoirs on the lower Snake River.

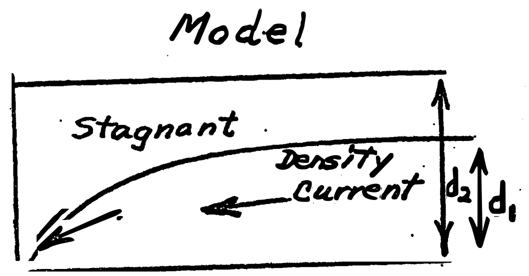
It is fortunate that we have both theoretical and full scale empirical evidence for a relationship between the thickness of the density current and the densiometric Froude number. We need full scale field measurements of internal currents for a variety of conditions to show the correct relationship for various types of reservoirs.

In the meantime, we will have to rely on the results of model studies. One advantage in the use of non-dimensional parameters such as the Froude number lies in the fact that the numerical relationships remain the same for any size of the scale of motion, providing that the physical processes (such as viscosity and surface tension) which are neglected in the Froude number do not assume major importance.

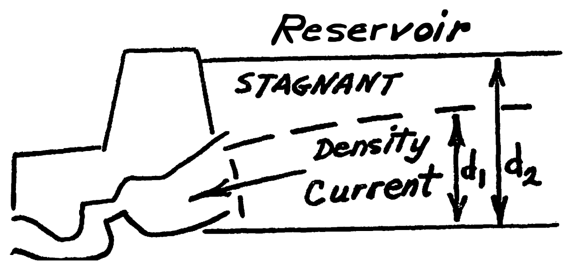
Debler (1959) supplies the information we need for this study. He made a very careful series of model tests at the Hydraulics Laboratory of the National Bureau of Standards Model Laboratory in Washinton, D. C. A vertical density structure was set up in the model by using colored layers of water with different densities. Water was then drawn off from a line sink across the bottom of one end of the flume tank. Different rates of discharge were used and the model photographed from the side. The photographs show the flow pattern as a density current flowing out through the outlet on the end of the flume.

Debler's model has the same conformation as that of the lowest Snake River reservoirs. Figure 5 shows a cross section of the model flume tank compared to a transverse section through a typical lower Snake River reservoir. In both situations the outlet is at the bottom

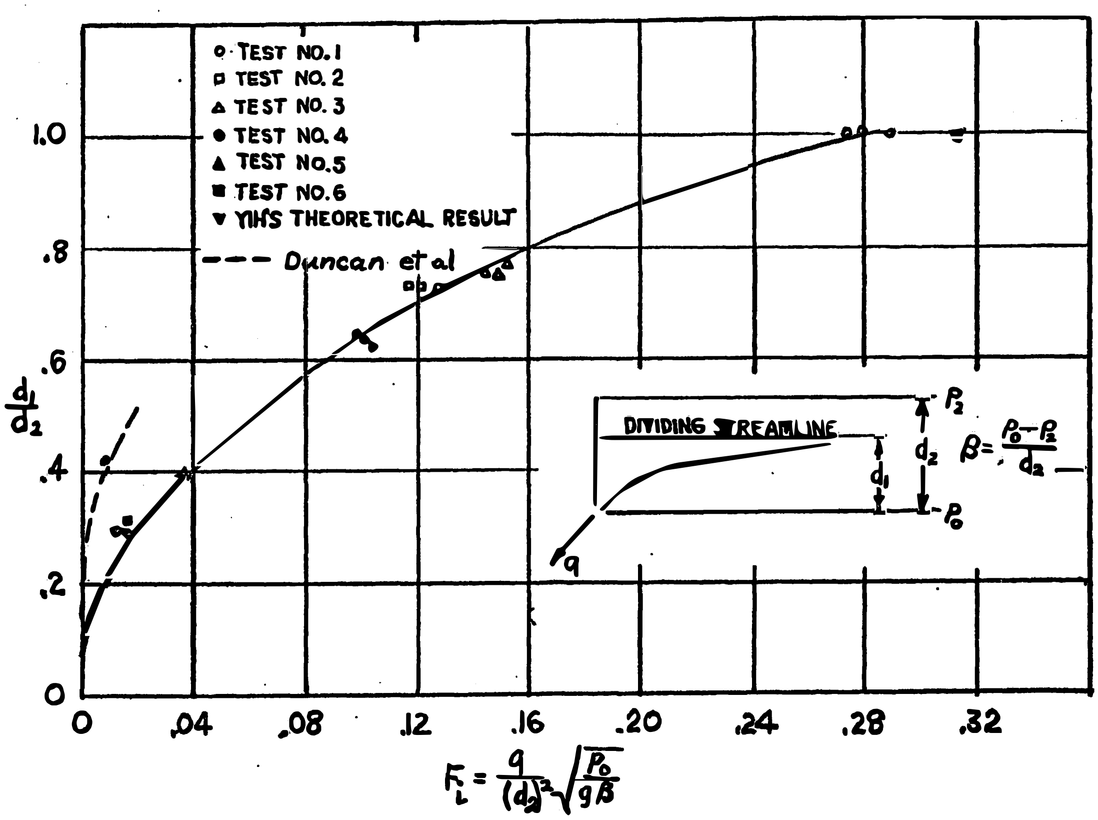
Figure 5.



a) Debler's model channel



b) Schematic diagram of density current in a stratified intermediate reservoir.



c) The ratio of the thickness of the density current to the depth of the channel (from Debler, 1959).

and the flow is restricted to elevations at or above the elevation of the bottom of the reservoir outlet or line sink of the model.

Note that Debler used d_2 the whole depth of the reservoir instead of Z_o (the depth to the centerline of the turbines used by Duncan et al, 1962). This difference in one of the depth parameters would add to the expected differences between Debler's relationship between F_i and d_1/d_2 and Duncan et al's. (1962) relationship between F_i and d/Z_o.

Figure 6 is redrawn from Figure 9 of Debler's paper. Debler's q is discharge per unit width of the model, or Q/W.

Debler ran his experiment through a large range in F_i up to the point where the flow extended all the way to the surface ($d_1/d_2 = 1$). The critical value of F_i was experimentally found to be 0.28 in good agreement with Yih's (1958) theoretical critical value of 0.318. On the lower part of the scale of F_i the values of d_1/d_2 are about half the values of d/Z_o found by Duncan et al. (1962). The over-all agreement between the results of the three investigations is remarkable, considering the differences in the three methods of approach.

Debler's (1958) relationship was applied to data for the Ice Harbor reservoir. The depth, d_2, was taken as 118 feet and the width, W, was taken as 2500 feet. The results are shown on Figure 2. The vertical scale on Figure 2 is the temperature difference between the surface and 100 feet, assuming that the surface temperature was 70°F. The horizontal scale is discharge in cubic feet per second. The curved lines on the graph are computed numerical values of the ratio d_1/d_2.

Example: At a discharge rate of 20,000 CFS and a temperature gradient of 2° F per hundred feet, what is the thickness of the current into the turbines? At the intersection between 20,000 CFS and 2° F, read 70%. 70% x 118 ft. = 83 ft.

Localized boundary conditions will cause differences between the actual flow in the reservoir and that predicted by Figure 2. The results will tend to make the actual thickness of the current greater than the predicted thickness due to turbulence effects. Vorticity will cause some disturbance right at the face of the dam with resulting turbulence and withdrawal from other than predicted depths.

Turbulence will increase the actual thickness of the current over that predicted for high flows with low thermal density gradients. The actual degree of increase in thickness can only be shown by current measurements in full scale reservoirs.

Despite the above limitation, the above can tell us a good deal about the expected flow pattern in the Ice Harbor and other low, lower Snake River reservoirs.