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HYDRAULICS OF STRATIFIED FLOW
FINAL REPORT
SELECTIVE WITHDRAWAL FROM RESERVOIRS

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16. ABSTRACT

Selective outlet works provide an important means by which the quality of water withdrawn from reservoirs may be controlled. This is the third and final report in a series, and is part of a continuing effort to develop accurate practicable design and operating criteria for such outlets. The studies discussed here refine previously developed analyses, including evalutation of previous simplifying assumption, such as a linear density gradient and equal half-layer discharges. A method is presented for predicting velocity destributions within a withdrawal layer. Layers restricted by either the water surface or reservoir bottom and unrestricted layers are considered. The method is compared with experimental and prototype data. Step-by-step design procedures are included.

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PURPOSE

The purpose of this report is to present recently achieved modifications to the previously presented tentative theory on selective withdrawal from stratified reservoirs. The author also attempts to develop and present the theory with design curves and formulas that are of practicable significance.

RESULTS

1. Attempts to correlate inaccuracies in withdrawal layer thickness prediction with variation in the density gradient from the assumed linear distribution proved inconclusive.

2. Dimensionless velocity distribution curves were developed for withdrawal layers that were either unrestricted or restricted by the bottom or the water surface. In these curves the dimensionless velocity term (the local velocity divided by the maximum velocity in the withdrawal layer) is correlated to the density gradient across the withdrawal layer and the relative location within the withdrawal layer.

3. It was generally observed that for withdrawal layers not restricted by the water surface or bottom, the elevation of the maximum velocity in the flow was the same as that of the center of the withdrawal outlet.

4. For withdrawal layers that are restricted by either the water surface or the bottom, the location of the maximum velocity was found to shift from the outlet centerline towards the restricting boundary. A curve to evaluate this shift was developed. The curve correlates the relative positions of the restricting boundary and the outlet centerline (with respect to the total withdrawal layer thickness) to the maximum velocity location.

5. A correlation between uneven discharge distributions within the withdrawal layer and the predicted half-layer thickness (distances from outlet centerline to layer boundaries) was developed for half layers that are not restricted by a boundary. It was found that variations from a uniform discharge distribution could be evaluated. These in turn could be used to develop modified discharges for use in evaluation of corrected withdrawal layer boundaries. This correction is only meaningful for unrestricted half layers. The thickness of the restricted half layers is established by physical limits and therefore cannot be modified.

APPLICATION

The material in this report is intended primarily for use by U.S. Bureau of Reclamation (USBR) designers in designing facilities for selective withdrawal from reservoirs. The contents should also be of interest to other researchers in this field. Emphasis is placed on the hydraulic engineering aspects of selective withdrawal.

INTRODUCTION

This third and final report completes a series dealing with the hydraulics of stratified flows as applied to selective withdrawal from reservoirs.

The studies described by these reports were initiated on the premise that many water quality parameters follow the patterns established by reservoir stratification. It was also realized that the quality of reservoir outflow could be controlled through selective withdrawal; however, knowledge of the mechanics of stratified flow and selective withdrawal was limited and more accurate predictive abilities were needed to optimize design and operation of selective withdrawal structures.

In the first report in this series [1]* D. L. King presented a summary of the basic theories and principles dealing with stratified flows and selective withdrawl. He also discussed hydraulic modeling problems which include similitude and modeling law questions as well as physical modeling facility and instrumentation difficulties. Finally, in the initial report King evaluated the state of research as of 1966 in which he not only presented a review of literature and a summary of USBR activities, but also an evaluation of areas needing additional research and a proposal for research by the Hydraulics Branch, Division of General Research of the USBR.

The second report in this series,[2] also by D. L. King, reviewed past research in reservoir stratification and selective withdrawal. He then presented a tentative theory for aiding in the solution of design and operational selective withdrawal problems. In his analysis King modified the formula for the densimetric Froude number as suggested by Debler.[3] This formula is:

$$F' = \frac{V}{\sqrt{g'd}} \; 0.28 \pm 0.04 \qquad (1)$$

*Superscript numbers refer to references listed at the end of this report.

where

- F' = densimetric Froude number
- V = average velocity in withdrawal layer
- g' = $g\,\Delta\rho/\rho$
- ρ_o = density at orifice centerline
- $\Delta\rho$ = density differential across layer
- d = thickness of withdrawal layer

He then developed equations of the general form:

$$F' = \frac{V_o}{\sqrt{g'd}} = K\frac{Wd}{D^2} \qquad (2)$$

where

- V_o = velocity through withdrawal orifice
- K = constant depending upon the shape of the withdrawal orifice and the value of the critical densimetric Froude number (selective withdrawal can be accomplished only for densimetric Froude numbers below the critical value)
- W = channel width
- d = withdrawal layer thickness above or below the orifice centerline
- D = diameter or vertical width of outlet.

King then rearranged terms to obtain:

$$\frac{D^4\,\rho_o\,V_o^2}{g} = \Delta\rho\,K^2\,d^3\,W^2 \qquad (3)$$

which is a convenient form of the equation that may be applied easily in digital computer solutions. This analysis, however, contains several assumptions and simplifications which limit the flexibility and accuracy of the method. The first of these assumptions is that the density gradient across each half layer is linear. In actuality, however, this is almost never the case. In many cases the deviation from linearity is extreme. A second and equally significant assumption is that the total discharge is equally divided between the upper and lower portions of the withdrawal layer. This assumption is probably erroneous in all cases where the density gradient is not balanced about the withdrawal centerline. However, this error is generally most severe in those cases involving surface or bottom interference. As King noted:

> When intersection with the reservoir bottom or water surface occurs, this assumption (equally divided discharge) is no longer valid. d is now less than the value required to satisfy equation (3). The discharge above or below the orifice is then adjusted by multiplying the discharge by the ratio of the right side to the left side of equation (3). The resulting excess discharge is applied to the other portion of the withdrawal layer.[2]

It is also noted that this discharge correction factor is probably not completely accurate. King recommended in the second report that future work should evaluate the velocity distribution in the withdrawal layer and that this information could be used to determine the discharge distribution in the layer. This could be done for cases both with and without water surface or bottom interference.

Because of the nature of the study, it was not possible to consider specific reservoir shapes and outlet configurations. These factors change from site to site and thus do not lend themselves to a generalized research study. The results of this analysis are therefore most applicable to straight, uniform reservoirs with relatively symmetrical and unrestricted outlet placements. The results of this study can be expected to be representative for many facilities. Highly sinuous reservoirs, reservoirs with severe constrictions, intake structures with indirect access to the reservoir, and other similar physical factors can be expected to reduce the accuracy of representation. It may also be desirable, in some cases, particularly for larger structures or structures for which the selective withdrawal ability is critical, to refine this analysis. Model studies of specific installations can consider factors that are beyond the scope of this study and therefore can provide accurate predictive capabilities and the most effective design.

In this, the third and final report, an attempt is made to develop more accurate predictive methods. This additional accuracy is gained through the development of modifications to the basic formula, equation (3). These modifications attempt to consider the effect of both deviations from a linear density gradient and deviations from an equal discharge distribution. This report also attempts to present design curves and procedures that are of practicable significance.

TEST FACILITY AND PROCEDURE

Figure 1 shows the flume used for the laboratory tests. A refrigeration system in the flume was used to create the density stratification. The strength of the stratification could be controlled easily by adjusting a control thermistor. The stratification was monitored and recorded by using a series of thermistor probes placed at desired locations in the test flume. The thermistors were connected through a scanning device to a digital thermometer and a printer where temperatures are displayed and recorded with an accuracy of 0.02°C.

Figure 1. Test flume and observation of withdrawal layer. Photo P801-D-74321

Two very accurate quartz probes, with a digital thermometer, were used for calibrating and checking the thermistor probes. Outflow from the flume occurred through a small orifice whose elevation was adjustable. The outflow was wasted and therefore not returned to the flume, resulting in a falling water surface in the test flume. When attempts were made to maintain a constant water surface elevation, data collection was more difficult because of extraneous currents established by the inflow. The withdrawal discharge was monitored with a differential mercury manometer across a volumetrically calibrated 3/8-inch-diameter orifice.

Temperature was selected instead of salinity as the agent for creating stratification for three principal reasons. First, temperature is a convenient medium for establishing and altering a stratified reservoir. Second, temperature stratification can be monitored easily with one set of probes. Because saline stratifications also contain temperature stratifications, a dual probe system with a superimposition of data is required to obtain the actual density gradient. Finally, temperature stratification creates a hydraulic model that more correctly represents the prototype molecular diffusion coefficient. As King noted:

> The molecular diffusion coefficient for heat is on the order of 500 times greater than that for sodium chloride. This would tend to increase the withdrawal layer thickness in the thermal heat models and thus decrease the apparent critical value of F '.[2]

The test procedure presented herein was followed for all data shown in this report. As soon as the test flume was freshly filled, the refrigeration unit was turned on and allowed to operate for at least 16 hours. After the stratification had been thus created, the refrigeration unit was switched off and the reservoir was allowed to stand for 3 to 4 hours. This period of time allowed currents to dissipate and the reservoir to stabilize. When the stabilization period was complete, the withdrawal layer was then given at least 20 minutes to develop and stabilize, after which data were collected. Crystals of potassium permanganate were dropped at a given station in the flume. At the same time a stopwatch was started. Then over a period of a few minutes the flow being withdrawn created a deformation in the vertical dye streak created by the falling crystals. The stopwatch was then stopped, and data were collected either visually or photographically. The data included: (1) average water surface elevation for the run, (2) upper and lower withdrawal layer boundary elevations, (3) elevation and magnitude of maximum dye streak deflection, (4) outlet elevation and discharge, (5) total time interval involved, and (6) average temperature profile for the run. Where photographic data were taken, total velocity distribution information resulted.

The test facility is a three-dimensional model although the reservoir shape has been idealized. The reservoir width is considered in all of the following analyses. Observations in the model indicate that the withdrawal layer quickly grows to its full thickness and to the full width of the reservoir. The layer thickness is nearly constant with respect to time and distance from the outlet when the density gradient is constant. Therefore, the analysis may be undertaken for any reservoir cross section considered to be representative.

EXPERIMENTAL FINDINGS

With No Bottom or Water Surface Interference

Initial efforts were directed toward improving the accuracy of withdrawal layer thickness prediction with the assumption of equal discharge distribution between the upper and lower layers accepted, while questioning the linear density gradient assumption. Noted was that if in the theoretical development something other than a linear gradient was assumed, a nonlinear differential equation developed. Solution of this equation would be difficult if not impossible. Therefore, attempts were made to develop coefficients based on the difference between the assumed linear and the true density gradients. The coefficients would be used to modify the results obtained from the conventional analysis so that more accurate solutions would be obtained. All of the attempts made proved to be futile.

Attention was shifted to the equal discharge distribution assumption and its effect on the analysis. A portion of the withdrawal layer data had been collected photographically, making it possible to obtain total velocity distribution information. The areas encompassed by the velocity distribution curve, both above and below the orifice centerline, were determined with a planimeter. From this the discharges both above and below the orifice centerline were determined. These discharges ranged from 25 to 75 percent of the total flow for cases where no bottom or water surface interference occurred. The conclusion was that some method should be found to predict the discharge distribution and to evaluate its effect on the withdrawal layer thickness calculation. Efforts were once again centered on the photographic velocity distribution data. Using the dimensionless parameters developed by Bohan and Grace,[4] the dimensionless velocity distribution curve, shown in Figure 2, was developed. These parameters are:

$$\frac{y\,\Delta\rho}{Y\,\Delta\rho_m} \text{ and } \frac{v}{V}$$

where:

- $\Delta\rho$ = density difference of fluid between the elevations of the maximum velocity and the corresponding local velocity.
- $\Delta\rho_m$ = Density difference of fluid between the elevations of the maximum velocity and either the upper or lower boundary (depends on which half of the withdrawal layer is being examined)
- y = the vertical distance from the maximum velocity to a point on the velocity distribution
- Y = the vertical distance from the maximum velocity to either the upper or lower limit of the zone of withdrawal
- v = the local velocity at y
- V = the maximum velocity in the zone of withdrawal.

Figure 2 also shows the dimensionless velocity distribution curve developed by Bohan and Grace and a few prototype date points. The prototype data points are from two sources: a Tennessee Valley Authority study of Fontana, Watts Bar, and Douglas Reservoirs [5] and a USBR study of Lake Mead.[6] Only a limited amount of prototype data is available; more would be required to obtain an accurate verification of the model data. Several sources of error, when combined, probably yield the data scatter in Figure 2. In the model tests these sources of error are:

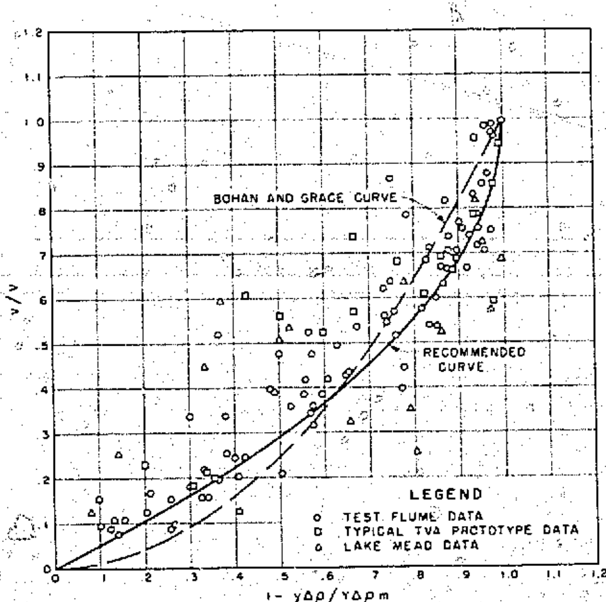


Figure 2. Velocity distribution in stratified flow with boundary effects negligible.

1. *Large model scale.*—The large model scale used either directly or indirectly reduced the data collection accuracy. The thicknesses of the withdrawal layers are so small that inaccuracies in the thickness measurement (including those due to parallax) may be significant.

2. *Secondary currents.*—The relatively small thickness of the withdrawal layer may be susceptible to errors induced by small secondary currents from several sources. These currents may be the single most important source of error in the analysis. Secondary currents can be caused by withdrawal from a restricted reservoir. Since the withdrawal layer has horizontal limits, a vertical flow must be established to supply water to the layer. Secondary currents can also develop when the dye is dropped into the flume. The dye-caused currents are due to both the disturbance caused by the falling crystals and to density currents caused by the dyed water.

3. *Falling water surface elevation.*—Returning water to the flume in an attempt to maintain a constant water surface elevation would induce strong secondary currents; therefore, no water was returned to the flume during these tests. These currents would no doubt have severely hampered, if not made impossible data collection. The reservoir water surface was allowed to fall as water was withdrawn.

Because the density profile of the reservoir changed constantly, data were collected for the average density profiles for the total number of runs. The withdrawal layer boundaries also were evaluated approximately for the average conditions. This changing water surface elevation is a possible source of additional scatter.

For the field tests the greatest source of data scatter, by far, is error caused by other extraneous currents in the reservoir. These currents result from tributary inflows; outflows through the various spillways, outlet works, and generating facilities; and atmospheric energy exchange (wind, heat, etc.). It would be virtually impossible to still these currents in a prototype reservoir. Possible scatter caused by these currents may be extremely significant.

By obtaining a dimensionless velocity distribution curve, a modified withdrawal layer thickness prediction can be undertaken. The elevation of the maximum velocity in the withdrawal layer must be known prior to making the analysis. Bohan and Grace[4] note that, "* * * the maximum velocity within the zone of withdrawal, in most cases, did not occur at the elevation of the orifice centerline" and that "Data analysis indicated that the maximum velocity occurred at the elevation of the orifice centerline only when the withdrawal zone was vertically symmetrical about the elevation of the orifice centerline. The maximum velocity occurred below the orifice centerline when the vertical extent of the lower limit of the withdrawal zone was less than that of the upper limit. Similarly, the maximum velocity occurred above the orifice centerline when the distance from the orifice centerline to the lower limit was greater than the distance from the orifice centerline to the upper limit." The author found a similar tendency in his data; but it was also noted that in cases where the bottom and water surface did not interfere with the withdrawal layer, the shift from the centerline was small. In these cases the assumption that the maximum velocity occurs at the elevation of the orifice centerline appears justified.

The recommended method of analysis for obtaining the withdrawal layer thickness consists of six steps:

1. *Basic theoretical prediction.*—The initial step consists of predicting the thickness of both the upper and lower portions of the withdrawal layer. This prediction is accomplished by using the digital computer program (Appendix) which applies the analysis that was developed by King[2] and summarized earlier in this report.

2. *Evaluate the dimensionless velocity distribution.*—By using the dimensionless velocity distribution curve, Figure 2, in conjunction with the assumed elevation of the maximum velocity (the outlet centerline elevation), the known reservoir density gradient data, and the withdrawal layer thickness information that was predicted in Step 1, the velocity distribution for the predicted withdrawal layer is evaluated.

3. *Integrate curves to determine discharge distribution.*—With this knowledge an integration of the velocity distribution curve is carried out, and unit width areas representative of the discharges both above and below the orifice centerline are evaluated. In this report the integration is done manually; however, this also can be computerized.

4. *Obtain modified discharges.*—To consider a shift from a uniform discharge distribution, modified discharges are developed for the computer program. The ratios of the upper and lower integrations to one-half of the total are first evaluated. These two ratios are then multiplied by the initial total discharge to obtain two modified total discharges.

5. *Obtain corrected layer thickness prediction.*—The modified discharges from Step 4 are then used instead of the initial assumed discharge as data for the computer program in Step 1. Thus, two program runs are made, each with exactly the same input data except for the discharges. The withdrawal layer boundary limits from the two runs are then united to yield a corrected withdrawal layer. The predicted upper boundary from the run using the discharge based on the upper ratio (Step 4) and the lower boundary from the run using the discharge based on the lower ratio (Step 4) form the new withdrawal layer limits.

6. *Obtain final layer thickness prediction.*—This method is convergent with additional applications of the steps. A process of successive approximations therefore can be applied until change in the predicted layer is negligible. The rate of convergence varies with the specific problem, but indications are that five or less cycles would be satisfactory. Observe also that the program used in Step 1 could

be modified to execute the entire analysis. Indications are that significant modifications to the initially predicted layer thickness occur only for cases with extreme variations from a balanced discharge distribution. In most cases the total modification will be only a small percentage of the initial thickness.

Sample Calculation With No Bottom or Surface Interference

The sample problem was obtained from TVA prototype data on Fontana Reservoir.[7] This is done so that the results can be compared to actual prototype observations, Figure 3.

The following information is used at the start of the analysis:

Water surface elevation = 1643 feet
Channel width = 1240 feet
Orifice diameter = 28 feet
Bottom elevation = 1363 feet
Orifice centerline elevation = 1456 feet
Withdrawal discharge = 6500 cfs

The additional reservoir information shown in Table 1 would also be known. The data that describe the reservoir in the problem are taken from Figure 3. As can be seen the full prototype reservoir depth was not modeled. It was realized that the withdrawal layer probably would not extend to either the water surface or bottom. So hypothetical bottom and water surface boundaries were used in the problem to reduce the amount of input data. If the predicted withdrawal layer reaches these hypothetical boundaries, then additional data would be input. As long as the predicted withdrawal layer does not reach the hypothetical boundary, the withdrawal layer will be the same whether the hypothetical boundaries or the actual boundaries are used in the computer program.

Step 1.—The known information is entered into the computer program as shown in the Appendix. The resulting withdrawal layer thicknesses are:

From centerline to upper limit = 41.1 feet
From centerline to lower limit = 32.8 feet

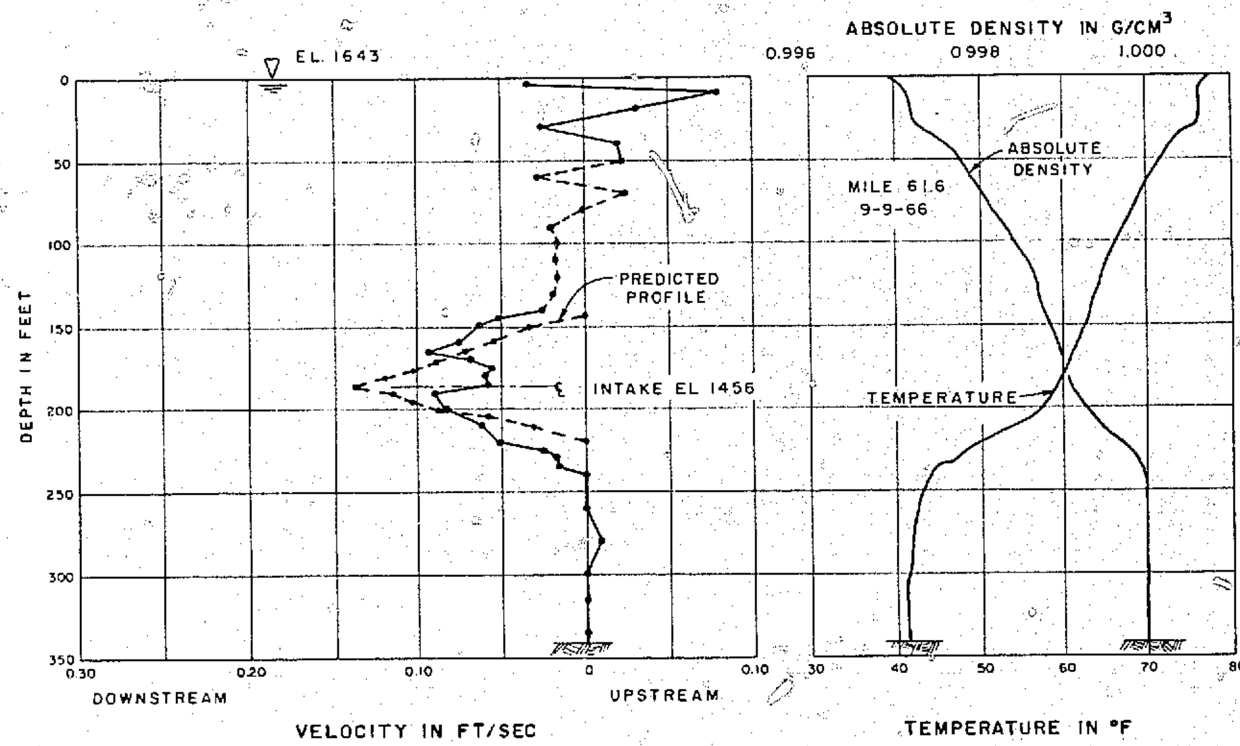


Figure 3. TVA prototype data for sample problem.

Table 1

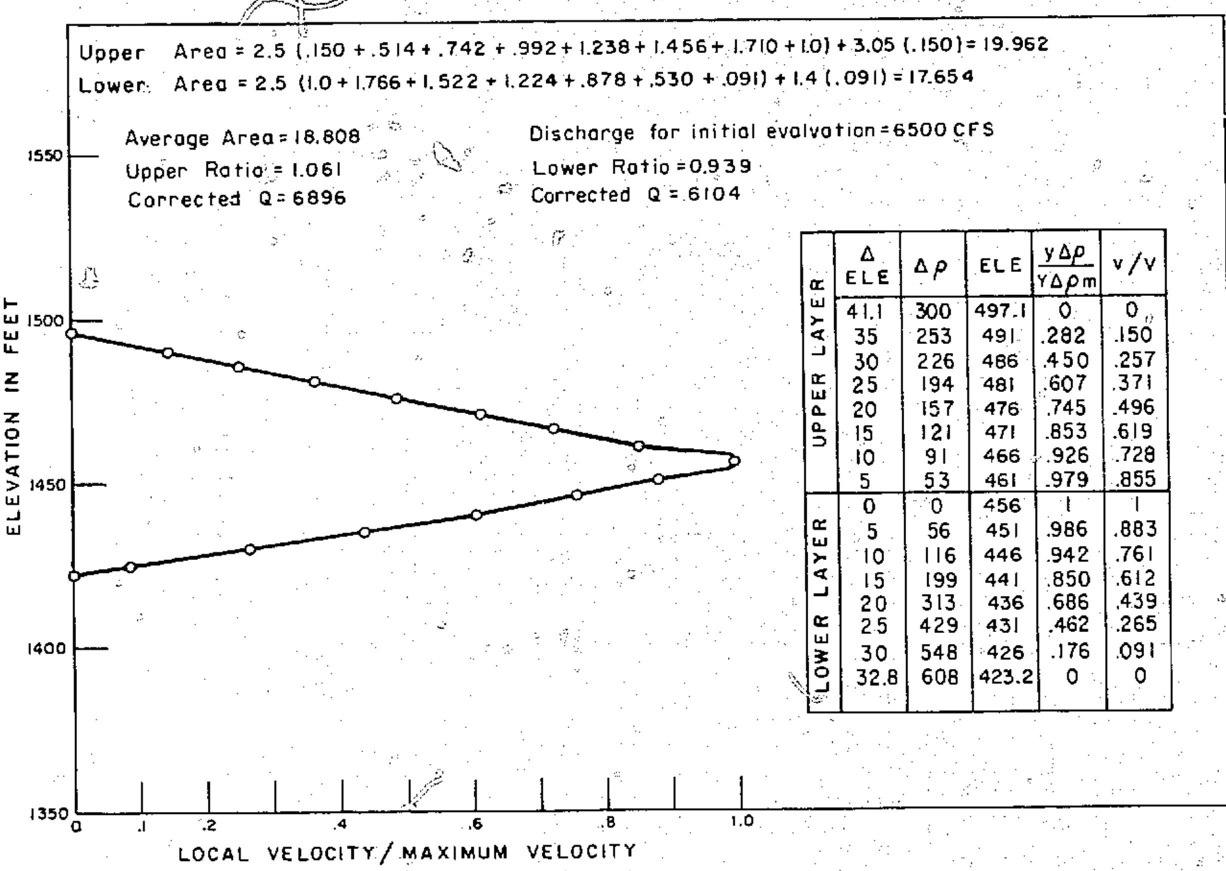
RESERVOIR DESCRIPTION

Elevation (feet)	Temperature (°F)	Elevation (feet)	Temperature (°F)
1363	41.9	1503	63.2
1373	42.2	1513	63.9
1383	42.5	1523	64.3
1393	43.1	1533	65.1
1403	44.3	1543	66.2
1413	47.0	1553	67.1
1423	50.4	1563	68.4
1433	54.4	1573	69.6
1443	57.5	1583	70.7
1453	59.0	1593	72.0
1463	60.2	1603	72.9
1473	60.9	1613	75.6
1483	61.7	1623	76.3
1493	62.3		

Step 2.—Develop the velocity distribution curve, figure 4. Since the elevation of the maximum velocity is assumed to be at the elevation of the outlet centerline, the upper layer thickness equals 41.1 feet and the lower layer thickness equals 32.8 feet. Random local elevations across the withdrawal layer may then be selected.

At these local elevations the densities and therefore the "$1-y\Delta\rho/Y\Delta\rho_m$" term may be evaluated. The velocity distribution curve, Figure 2, is used to obtain the dimensionless velocity distribution term (local velocity divided by the maximum velocity) at that elevation for plotting on Figure 4.

Step 3.—Integrate the areas contained between the maximum velocity elevation and the upper and lower boundaries of the velocity distribution curve, Figure 4. These terms are directly proportional to the discharges because the dimensionless velocity term is directly proportional to the local velocity.



	Δ ELE	Δρ	ELE	$y\Delta\rho / Y\Delta\rho_m$	v/V
UPPER LAYER	41.1	300	497.1	0	0
	35	253	491	.282	.150
	30	226	486	.450	.257
	25	194	481	.607	.371
	20	157	476	.745	.496
	15	121	471	.853	.619
	10	91	466	.926	.728
	5	53	461	.979	.855
LOWER LAYER	0	0	456	1	1
	5	56	451	.986	.883
	10	116	446	.942	.761
	15	199	441	.850	.612
	20	313	436	.686	.439
	25	429	431	.462	.265
	30	548	426	.176	.091
	32.8	608	423.2	0	0

Figure 4. Sample problem, no boundary effect.

Step 4.—Divide the area terms evaluated in Step 3 by the average of their two values. This yields the two discharge ratio terms (upper and lower layer) that, when multiplied by the initial discharge of 6,500 cfs, yield the upper and lower corrected discharges. For this problem the corrected upper discharge is 6,896 cfs, and the corrected lower discharge is 6,104 cfs.

Step 5.—The computer runs as in Step 1 are now made using the discharges from Step 4. The 6,896 cfs yields an upper half-layer depth of 42.3 feet, and the 6,104 cfs yields a lower half-layer depth of 31.9 feet.

Step 6.—One more cycle was computed through; the resulting upper half-layer depth was 42.9 feet, and the resulting lower half-layer depth was 31.4 feet. The predicted and observed results are shown on Figure 3.

By dividing the area contained within the entire dimensionless velocity distribution curve by the discharge for a unit width of reservoir, the maximum velocity may be determined. The dimensionless velocity term and therefore the area contained within the dimensionless velocity distribution curve are linearly proportional to the true velocity, and the term of proportionality is the maximum velocity. From the maximum velocity, the total velocity distribution may be easily determined. For the sample problem, the volume defined by the dimensionless velocity distribution curve with a unit width was approximately 38 cubic feet and the discharge for a unit width of reservoir was 5.24 cfs. The maximum velocity therefore would be 5.24/38 or 0.137 fps.

This computed maximum velocity compares to an observed maximum velocity of 0.09 fps which is reasonable agreement in view of the rather complex prototype velocity profile. A comparison of the predicted and observed profiles is shown in Figure 3.

With Bottom or Water Surface Interference

A similar evaluation was undertaken for cases in which either the bottom or the water surface interfered with the withdrawal layer. Once again, attempts to modify the theory so that nonlinear density gradients would be considered proved futile. So efforts were again shifted to an attempt to evaluate the significance of the discharge distribution assumption. As was noted earlier in the report, King[2] recommended the use of a discharge distribution factor developed from the ratio of the two sides of equation (3) at the boundary layer. The extent of the half layer that is affected by the boundary is set by the physical dimensions (boundary and outlet elevations). Any correction to the initially predicted thicknesses must therefore be limited to the half layer that is not interfered with.

A dimensionless velocity distribution curve was developed in a manner similar to the no-interference case. Photographs of the withdrawal layer were analyzed and a curve, Figure 5, based on the parameters proposed by Bohan and Grace[4] was developed. These parameters are quite similar to, but not the same as, the ones used in the no-interference case, Figure 2. The curve developed by Bohan and Grace is also shown in Figure 5. No prototype velocity-distribution data were available to use in verifying these curves.

Once again the probable elevation of the maximum velocity was needed. Again the maximum velocity generally was located on the same side of the outlet centerline as the thinner layer and, therefore is usually on the same side as the restricting boundary. In this case the distance from the maximum velocity to the outlet centerline was significant enough to evaluate. To develop a curve that would aid in predicting the maximum velocity location, dimensionless parameters, as proposed by Bohan and Grace,[4] were utilized. These parameters were:

$$\frac{Y}{H} \text{ and } \frac{Z}{H}$$

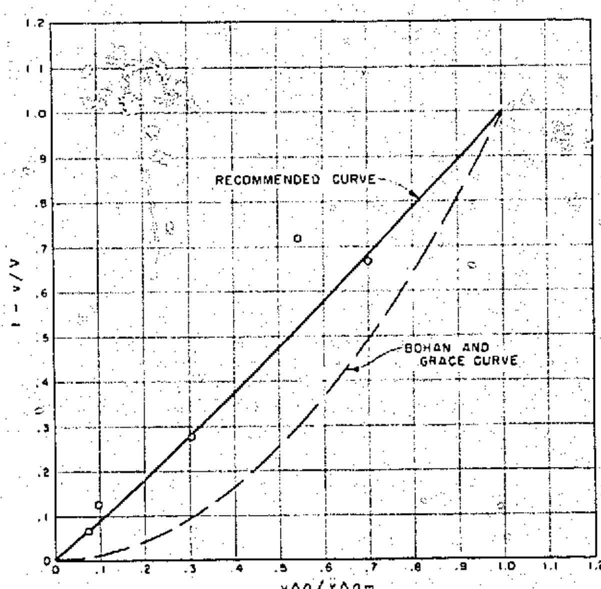


Figure 5. Velocity distribution in stratified flow with boundary effects.

ıere:

Y = the distance from the outlet centerline to the boundary
Z = the distance from the maximum velocity to the boundary
H = the height of the total withdrawal layer.

he curve that was developed is shown in Figure 6.

ith the knowledge of the outlet centerline elevation, e restricting boundary elevation, and the total ithdrawal layer thickness as predicted from the rocedure developed by King;[2] the elevation of the aximum velocity may be estimated. The commended sequence of analysis is quite similar to at recommended for the no-boundary interference se as follows:

1. *Basic theoretical prediction.*—Once again the method of King[2] is used to predict the thickness of the upper and lower halves of the boundary layer. Note that one of these half-layer thicknesses is set by the locations of the boundary and the outlet.

2. *Determine assumed discharge distribution.*—Each side of equation (3) is evaluated at the restricting boundary. The ratio of the right side to the left side of equation (3) is then multiplied by one-half of the total discharge to determine the predicted discharge in the restricted half layer. The difference between this discharge and the total discharge is the assumed discharge for the unrestricted half layer.

3. *Prediction of maximum velocity elevation.*—With the knowledge of the outlet centerline elevation, the restricting boundary elevation, and the total withdrawal layer thickness as predicted in Step 1, the maximum velocity location is determined from Figure 6.

4. *Evaluate the dimensionless velocity distribution.*—By using the dimensionless velocity distribution curve, Figure 5, in conjunction with the elevation of the maximum velocity (as predicted in Step 3), the known reservoir density gradient data, and the known restricted half withdrawal layer thickness, the dimensionless velocity distribution is evaluated for the restricted half layer. Then by using the no-interference dimensionless velocity distribution curve, Figure 2, in conjunction with the elevation of the maximum velocity (as predicted in Step 3), the known reservoir density gradient data, and the known thickness of the unrestricted withdrawal half layer (as predicted in Step 1), the dimensionless velocity distribution is evaluated for the unrestricted half layer. The two half-layer dimensionless velocity distributions are then combined to form a total layer curve. With this the velocity distribution is evaluated for the entire layer.

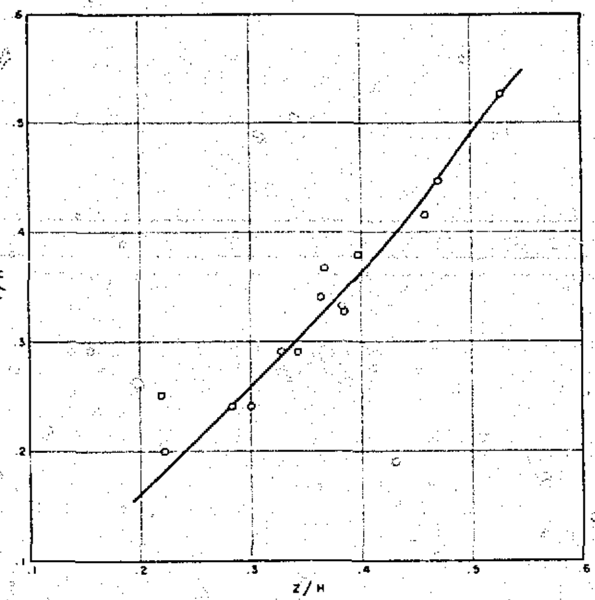


Figure 6. Relative position of maximum velocity for conditions in which a boundary limits the withdrawal zone.

5. *Integrate curves to determine discharge distribution.*—The velocity distribution curve may then be integrated. In this manner the discharges both above and below the orifice centerline are evaluated.

6. *Determine modified discharge.*—A modified discharge is then determined for the unrestricted half layer. This discharge is the summation of restricted half-layer discharge as evaluated in Step 2 and the unrestricted half-layer discharge as evaluated in Step 5. This term is placed in the digital computer program of Step 1 and the cycle started again. No modified discharge is needed for the restricted half layer because its thickness is established by the physical parameters.

7. *Obtain final withdrawal layer thickness prediction.*—Once again the solution converges. The above six steps therefore may be applied until a satisfactorily accurate answer is obtained.

Sample Calculation With Bottom or Surface Interference

The following information (from a model test run) is known at the start of the analysis:

Water surface elevation = 1.57 feet
Channel width = 3.00 feet
Orifice diameter = 0.0417 feet
Bottom elevation = 0.00 feet
Orifice centerline elevation = 1.50 feet
Withdrawal discharge = 0.00690 cfs

The reservoir information given in Table 2 would also be known.

Table 2

RESERVOIR DESCRIPTION

Elevation (feet)	Temperatures (°C)	Density (GR/CC)
0.033	9.84	0.9997407
0.167	9.93	.9997334
0.300	10.03	.9997249
0.433	10.13	.9997154
0.567	10.28	.9997011
0.700	10.44	.9996860
0.833	10.65	.9996660
0.967	10.90	.9996424
1.100	11.28	.9996026
1.233	12.38	.9994788
1.367	15.80	.9990013
1.500	19.94	.9982442

Step 1.–The known information is entered into the computer program as shown in Appendix 1. The resulting predicted withdrawal layer thicknesses are:

From centerline to upper limit = 0.07 feet
From centerline to lower limit = 0.24 feet

It should be observed that the withdrawal layer extends to, and therefore is restricted by, the water surface.

Step 2.–Evaluation of the left side of equation (3) yields:

$$\frac{D^4 \rho_o V_o^2}{g} = \frac{(0.0417)^4 (0.998244) (5.05)^2}{32.2}$$

or 0.00000239

and evaluation of the right side of equation (3) yields:

$$(\Delta\rho)(K^2)(d^3)(W^2) =$$

$$(0.998244-0.997774)(0.254)^2 (0.07)^3 (3)^2$$

or 0.0000000935

The ratio of the two is 0.0391. This yields an estimated discharge of (0.0391) (0.00690) or 0.000135 cfs in the restricted half layer. This would make the unrestricted discharge (0.00690–.0000135) or 0.006765 cfs.

Step 3.–The elevation of the maximum velocity is now predicted. It is known that:

$Z = 0.07$ feet
$H = 0.31$ feet

so, $Z/H = 0.225$

In referring this to Figure 6, it is observed that $Y/H = 0.18$ and Y is therefore 0.058 feet. This means that the maximum velocity is 0.012 feet above the outlet centerline at an elevation of 1512 feet.

Step 4.–The problem then is to determine the velocity distribution across the entire layer. Following the calculation procedures as shown on Figure 7, the dimensionless velocity distribution is obtained for the entire withdrawal layer.

Step 5.–The dimensionless curve obtained in Step 4 is then integrated to determine not only the discharge distribution for flow above and below the outlet centerline but also the maximum velocity. The calculation procedure for evaluating the unrestricted discharge is shown on Figure 7. As for the maximum velocity, once again the ratio of the unit width discharge to the integral of the entire dimensionless velocity curve is the maximum velocity.

Step 6.–The modified discharge for the unrestricted half-layer thickness calculation is then evaluated. With the restricted half-layer discharge of 0.000135 cfs from Step 2 and the unrestricted half-layer discharge of 0.00475 cfs from Step 5, the modified discharge is 0.004885 cfs. This is then inserted into the program of Step 1.

After two applications of this cycle the unrestricted half-layer thickness is predicted as 0.20 feet. The total withdrawal layer thickness is 0.27 feet. This compares to an observed thickness of 0.32 feet during the laboratory test.

Area above center line = [(.02)(.564) + (.01)(.564 + .765) + (.01)(.765 + .896) + (.018)(.896 + 1.) + (.012)(1. + .965)] / 2. = 0.0987

Area below center line = [(.05)(.965 + .732) + (.083)(.732 + .378) + (.067)(.378 + .134) + (.04)(.134)] / 2. = 0.2165

The lower discharge is therefore (0.2165/0.3152) or 0.688 of the total

Lower discharge = (0.688)(0.0069) = 0.00475 cfs

UPPER LAYER

Δ ELE	$\Delta\rho$	ELE	$\frac{y\Delta\rho}{Y\Delta\rho m}$	1-v/V	v/V
.058	4311	1.570	1	1	0
.038	2947	1.550	.448	.436	.564
.028	2238	1.540	.251	.235	.765
.018	1564	1.530	.113	.104	.896
.000	0	1.512	0	0	1.0

LOWER LAYER

Δ ELE	$\Delta\rho$	ELE	$1-\frac{y\Delta\rho}{Y\Delta\rho m}$	v/V
.000	0	1.512	1	1
.062	3461	1.450	.929	.732
.145	7964	1.367	.615	.378
.212	10533	1.300	.255	.134
.252	11899	1.260	0	0

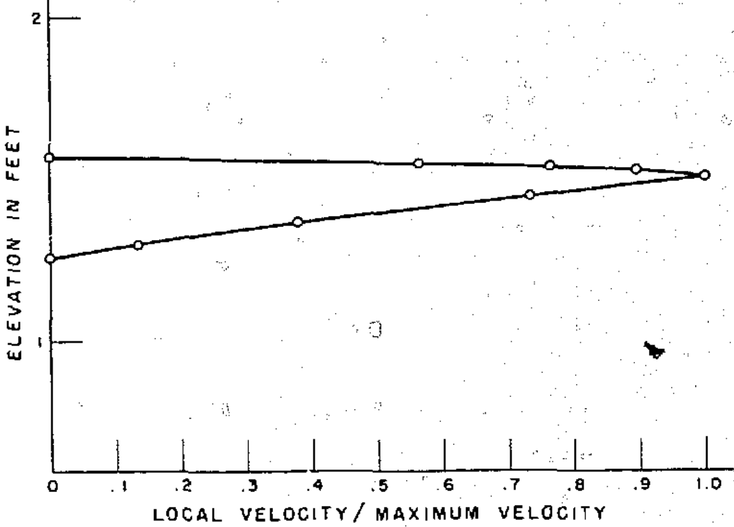


Figure 7. Sample problem with boundary effects.

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BUREAU OF RECLAMATION ENGINEERING COMPUTER SYSTEM

CLASSIFICATION - HYDRAULICS

USER'S MANUAL - PRO 1530-STRAT

PROGRAM BY

D.L.KING

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

DIVISION OF GENERAL RESEARCH

HYDRAULICS BRANCH

ENGINEERING AND RESEARCH CENTER

DENVER, COLORADO 10/11/73

T A B L E   O F   C O N T E N T S

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PROGRAM TITLE

SELECTIVE WITHDRAWAL LAYER THICKNESS COMPUTATION

GENERAL INFORMATION

THE SUBJECT COMPUTER PROGRAM WAS DEVELOPED PRIMARILY FOR DETERMINING THE THEORETICAL WITHDRAWAL LAYER THICKNESSES FOR STRATIFIED RESERVOIRS. THIS PROGRAM WAS INITIALLY DEVELOPED TO AID WITH MODEL STUDIES, BUT IT IS EQUALLY APPLICABLE TO INVESTIGATION OF PROTOTYPE STRUCTURES.

THE PROGRAM IS WRITTEN IN THE FORTRAN IV LANGUAGE FOR A HONEYWELL 800 COMPUTER. IT CAN BE USED WITH EITHER SQUARE OR ROUND WITHDRAWAL OUTLET SHAPES, WITH ANY OUTLET ELEVATION, RESERVOIR WIDTH, RESERVOIR DEPTH, AND OUTFLOW DISCHARGE. THE PROGRAM AS IT NOW EXISTS CAN BE USED WITH WATER TEMPERATURES BETWEEN 0 AND 30 DEGREES C. ALSO NO CONSIDERATIONS ARE GIVEN TO OTHER CAUSES OF DENSITY VARIATION (SUCH AS SALINITY AND TURBIDITY).

THE WITHDRAWAL LAYER THICKNESSES ARE COMPUTED USING EQUATION (17) FROM HYD-595 (EQ.3 OF THIS REPORT). THE LEFT TERM IS FIRST EVALUATED FOR THE PARTICULAR OUTLET CONDITIONS. THE PROGRAM THEN SEARCHES FOR THE TWO DEPTHS AT WHICH THE RIGHT HAND TERM

SATISFIES THE EQUALITY. THESE TWO DEPTHS ARE THE UPPER AND LOWER LIMITS OF THE WITHDRAWAL LAYER

THE COMPUTATION IS CARRIED FORWARD IN A SERIES OF STEPS AS SHOWN IN THE ACCOMPANYING FLOW CHART, BEGINNING WITH THE CORRECTION OF THE TEMPERATURE READINGS FOR THE VARIOUS LEVELS (THIS CAN BE OMITTED BY REMOVING THREE STATEMENTS FROM THE PROGRAM). WITH THE CORRECT TEMPERATURES THE DENSITIES ARE THEN COMPUTED. THE LEFT HAND TERM IS THEN EVALUATED FOR THE PARTICULAR OUTLET CONDITIONS. THE PROGRAM THEN EVALUATES THE RIGHT HAND TERM AT EACH TEMPERATURE LEVEL STARTING FROM THE HIGHEST. THESE VALUES ARE THEN COMPARED TO THE LEFT HAND TERM UNTIL THE POINT OF EQUALITY IS PASSED. THAT INTERVAL IS THEN BROKEN INTO 100 INCREMENTS AND AGAIN THE RIGHT HAND TERMS ARE COMPUTED AND COMPARED TO THE LEFT HAND TERM UNTIL THE POINT OF EQUALITY IS AGAIN PASSED. THE POSITION OF THE UPPER LIMIT OF WITHDRAWAL IS THUS OBTAINED. A SIMILAR PROCEDURE IS THEN EXECUTED TO OBTAIN THE LOWER BOUNDARY. THE PROGRAM WILL COMPENSATE FOR CASES IN WHICH EITHER THE WATER SURFACE OR THE BOTTOM IS LOCATED IN WHAT WOULD OTHERWISE BE THE COMPUTED WITHDRAWAL LAYER. ALSO IT WILL SOLVE CASES IN WHICH THE UPPER AND LOWER BOUNDARIES ARE BOTH BETWEEN THE SAME TEMPERATURE LEVELS.

INPUT

THE FIRST 31 DATA CARDS CONTAIN CORRESPONDING VALUES OF

TEMPERATURE AND DENSITY FOR TEMPERATURES FROM 0 TO 30 DEGREES C, IN ONE DEGREE INCREMENTS. THESE DATA ARE PLACED IN COLUMNS 1-16 IN AN 8-COLUMN FORMAT, WITH THE POSITION OF THE DECIMAL POINT UNSPECIFIED (8F.0)

THE PROGRAM AS WRITTEN FOR ANALYSIS OF MODEL DATA SPECIFIES 28 CARDS TO FOLLOW, WHICH CONTAIN CORRECTION VALUES FOR THE THERMISTOR READINGS. THIS CORRECTION IS DELETED BY ELIMINATING STATEMENTS 0006, 0007, AND 0014 FROM THE PROGRAM (SEE PROGRAM LISTING).

THE NEXT DATA CARD CONTAINS THE VARIABLES OF RESERVOIR WIDTH, OUTLET SIZE, WATER SURFACE ELEVATION, BOTTOM ELEVATION, AND OUTLET SHAPE IN COLUMNS 1-40, WITH AN 8F.0 FORMAT. COLUMNS 41 AND 42 CONTAIN THE VALUE OF THE NUMBER OF ELEVATION - TEMPERATURE CARDS TO FOLLOW, IN A I2 INTEGER FORMAT.

THE REMAINING CARDS CONTAIN CORRESPONDING VALUES OF ELEVATION AND TEMPERATURE (IN DEGREES C).

NO SUBROUTINES ARE USED IN THIS PROGRAM. APPENDIX B CONTAINS AN EXAMPLE PROBLEM IN WHICH THE DATA IS SHOWN AS IT WOULD BE ENTERED INTO THE PROGRAM.

SUBMITTAL INSTRUCTIONS

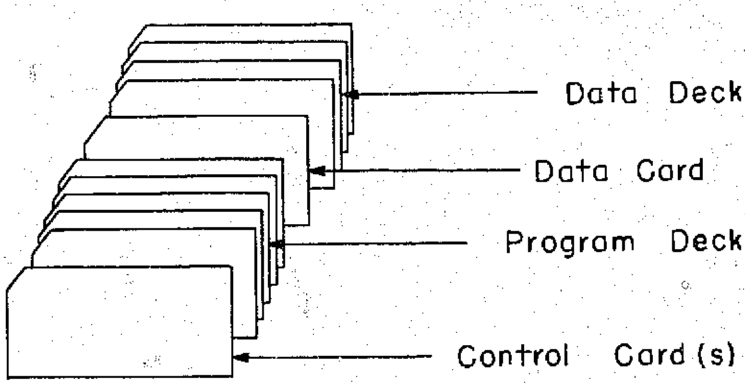
THE DECK SHOULD BE STACKED ACCORDING TO THE DIAGRAM IN APPENDIX A.

OUTPUT

PRINTED OUTPUT CONSISTS OF: 1. LISTING OF THE ELEVATION ABOVE THE BOTTOM, THE CORRECTED TEMPERATURE AT THAT LEVEL, AND THE DENSITY AT THAT LEVEL 2. SHAPE OF THE OUTLET (SQUARE OR CIRCULAR) 3.THE OUTLET SIZE 4.THE OUTLET ELEVATION 5.THE DISCHARGE 6.THE UPPER LIMIT OF WITHDRAWAL 7.THE LOWER LIMIT OF WITHDRAWAL. AN EXAMPLE OF THIS PRINTED OUTPUT IS SHOWN IN THE SAMPLE PROBLEM (APPENIX B). WHEN PROTOTYPE DATA ARE USED, THE FORMAT FOR PRINTING THE DISCHARGE MUST BE MODIFIED (FOR EXAMPLE, FROM F8.5 TO F8.0).

APPENDIX A

THE FOLLOWING FIGURE ILLUSTRATES THE CORRECT ORGANIZATION OF THE INPUT DATA DECK.



DECK ARRANGEMENT

APPENDIX B

THE FOLLOWING EXAMPLE PROBLEM IS GIVEN TO ILLUSTRATE HOW TO USE THE PROGRAM. SHOWN IN FIGURE 1 IS THE EXAMPLE PROBLEM DISCRIPTION. FIGURE 2 SHOWS THE INPUT DATA SHEET AND FIGURE 3 SHOWS THE OUTPUT OBTAINED.

At the beginning of this example problem the following information was known:

Water Surface Elevation = 322 feet
Channel Width = 1,240 feet
Orifice Diameter = 28 feet
Bottom Elevation = 62 feet
Orifice Centerline Elevation = 155 feet
Withdrawal Discharge = 6,500 cfs

The following reservoir information would also be known.

Elevation (feet)	Temperature (°C)	Elevation (feet)	Temperature (°C)
62	5.50	192	16.83
72	5.67	202	17.33
82	5.83	212	17.72
92	6.17	222	17.94
102	6.83	232	18.39
		242	19.00
112	8.33	252	19.55
122	10.22		
132	12.44	262	20.22
142	14.16	272	20.89
152	15.00	282	21.50
		292	22.22
162	15.67	302	22.72
172	16.05	312	24.22
182	16.50	322	24.61

Figure 1. Example problem.

We wish to find the predicted withdrawal layer.

The input data for the program would be arranged as follows:

EL-22
(5-63)

BUREAU OF RECLAMATION

LABORATORY PUNCH CARD DATA

USE / COLORED CARDS			
PROBLEM		JOB NO.	
DETAIL	Input Data For Sample Problem	#	
FEATURE		RETURN TO	
PROJECT		ROOM	BLDG. PHONE

1–8	9–16	17–24	25–32	33–40	41–48	49–56	57–64	65–72	73–80
1240.	28.	322.	62.	.065	2.7				
62.	5.50								
72.	5.67								
82.	5.83								
92.	6.17								
102.	6.83								
112.	8.33								
122.	10.22								
132.	12.44								
142.	14.16								
152.	15.00								
167.	15.67								
172.	16.05								
182.	16.50								
192.	16.83								
202.	17.33								
212.	17.72								
222.	17.94								
232.	18.39								
242.	19.00								

REMARKS

BY | DATE | CHECKED | SHEET 1 OF 2

Figure 2. Input data.

GPO 833957

EL-22
(5-63)

BUREAU OF RECLAMATION

LABORATORY PUNCH CARD DATA

USE	PROBLEM	JOB NO.	
	DETAIL	#	
COLORED CARDS	FEATURE	RETURN TO	
	PROJECT	ROOM	BLDG. PHONE

1–8	9–16	17–24	25–32	33–40	41–48	49–56	57–64	65–72	73–80
252.	19.55								
262.	20.22								
272.	20.89								
282.	21.50								
292.	22.22								
302.	22.72								
312.	24.22								
322.	24.61								
155.	6500.0								

REMARKS

BY | DATE | CHECKED | SHEET 2 OF 2

GPO 833769

Figure 2. Input data.

ELEVATION	TEMP	DENSITY
62.00	5.50	.99998
72.00	5.67	.99998
82.00	5.83	.99997
92.00	6.17	.99996
102.00	6.83	.99994
112.00	8.33	.99985
122.00	10.22	.99971
132.00	12.44	.99947
142.00	14.16	.99925
152.00	15.00	.99913
162.00	15.67	.99902
172.00	16.05	.99896
182.00	16.50	.99889
192.00	16.83	.99883
202.00	17.33	.99874
212.00	17.72	.99867
222.00	17.94	.99863
232.00	18.39	.99855
242.00	19.00	.99843
252.00	19.55	.99832
262.00	20.22	.99819
272.00	20.89	.99804
282.00	21.50	.99791
292.00	22.22	.99775
302.00	22.72	.99763
312.00	24.22	.99727
322.00	24.61	.99717

```
CIRCULAR OUTLET

OUTLET SIZE=  28.000 DISCHARGE= 6500.00
OUTLET ELEV=  155.00 UPPER LIMIT=  196.10 LOWER LIMIT=  122.20
```

Figure 3. Program output.

APPENDIX C

THE FOLLOWING IS A LISTING OF THE SUBJECT PROGRAM.

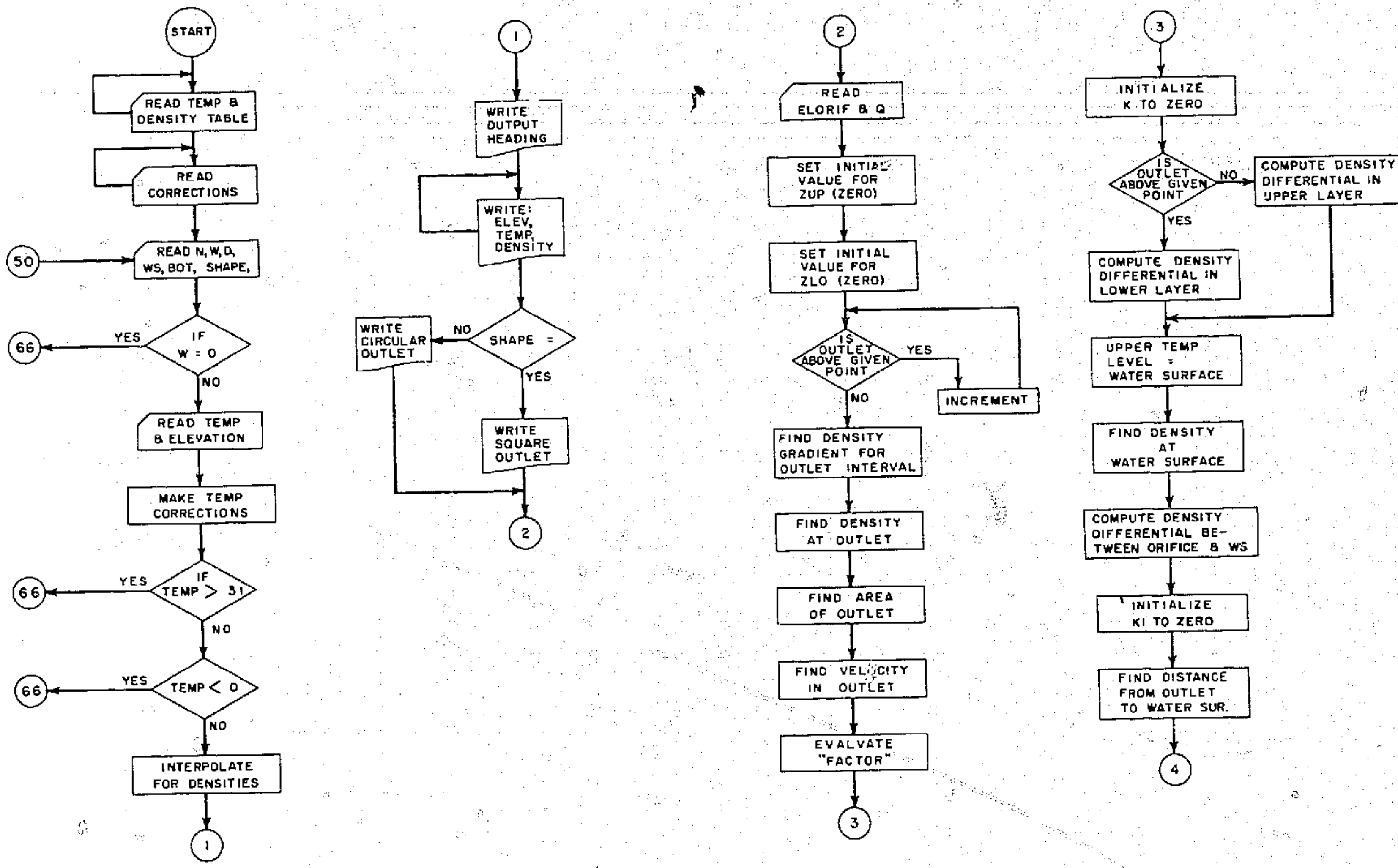
```
      C     COMPUTATION OF WITHDRAWAL LAYER THICKNESS                      1
            DIMENSION H(50),T(50),R(50),DELRU(50),DELRL(50),C(50),         2
           1TEMP(50),DENS(50)                                              2A
          1 FORMAT (5F8.0,I2)                                              3
          2 FORMAT (2F8.0)                                                 4
            DO 200 J=1,31                                                  5
        200 READ (2,2) TEMP(J),DENS(J)                                     6
            DO 9  I=1,28                                                   6A
          9 READ (2,2) C(I)                                                6B
         50 READ (2,1) W,D,WS,BOT,SHAPE,N                                  6
            IF (W .EQ. 0.0) GO TO 66                                       6AA
          7 DO 10 I=1,N                                                    7
            READ (2,2) H(I),T(I)                                           7A
            T(I)=T(I)+C(I)                                                 7AA
            IF (T(I).GT.31.) GO TO 66                                      7BB
            IF (T(I).LT.0.) GO TO 66                                       7CC
            DO 210 J=2,31                                                  7B
            TEM1=TEMP(J)                                                   7C
            TEM2=TEMP(J-1)                                                 7D
            DEN1=DENS(J-1)                                                 7E
            DEN2=DENS(J)                                                   7EE
            IF (T(I).GT.TEM1) GO TO 210                                    7FF
            IF (T(I).LT.4.) GO TO 215                                      7GG
            R(I)=DEN1-(T(I)-TEM2)*(DEN1-DEN2)                              7HH
            GO TO 10                                                       7G
        215 R(I)=DEN1+(T(I)-TEM2)*(DEN2-DEN1)                              7II
            GO TO 10                                                       7I
        210 CONTINUE                                                       7J
         10 CONTINUE                                                       8
            WRITE (3,52)                                                   8A
         52 FORMAT (1H1,1X,24H ELEVATION TEMP  DENSITY)                    8B
            DO 54 I=1,N                                                    8C
         54 WRITE (3,55) H(I),T(I),R(I)                                    8D
         55 FORMAT (F8.2,F8.2,F8.5)                                        8E
            IF (SHAPE .EQ. 0.040) GO TO 75                                 8F
            WRITE (3,70)                                                   8G
         70 FORMAT (1H0,16H CIRCULAR OUTLET)                               8H
            GO TO 11                                                       8I
         75 WRITE (3,76)                                                   8J
         76 FORMAT (1H0,14H SQUARE OUTLET)                                 8K
         11 READ (2,2) ELORIF,Q                                            9
            ZUP=0.0                                                        10A
            ZLO=0.0                                                        10B
            DO 15 I=1,N                                                    11
            IF (ELORIF .GT. H(I)) GO TO 15                                 12
            GRAD=(R(I-1)-R(I))/(H(I)-H(I-1))                               12A
            RORIF=R(I-1)-GRAD*(ELORIF-H(I-1))                              13
            AORIF=3.1416*D*D/4.                                            14
            VORIF=Q/AORIF                                                  15
            FACTOR=D**4*RORIF*VORIF**2/32.174                              16
            GO TO 16                                                       17
         15 CONTINUE                                                       18
      C     LIMITS OF WITHDRAWAL                                           19
         16 K=0                                                            20
            DO 20 I=1,N                                                    21
            IF (ELORIF .GT. H(I)) GO TO 21                                 22
```

```
            DELRU(I)=RORIF-R(I)                                          23
            GO TO 20                                                     24
         21 DELRL(I)=R(I)-RORIF                                          25
         20 CONTINUE                                                     26
            H(N+1)=WS
            R(N+1)=R(N)+(R(N)-R(N-1))*(WS-H(N))/(H(N)-H(N-1))
            DELRU(N+1)=RORIF-R(N+1)                                      26A
            K1=0                                                         26B
            ZUPP=WS-ELORIF                                               2
            PRODUP=DELRU(N+1)*SHAPE*ZUPP**3*W**2                         26D
            IF(PRODUP.GT.FACTOR)GOTO22                                   26E
            QUP=(Q*PRODUP/FACTOR)/2.0                                    26F
            QLO=Q-QUP                                                    26G
            SHAPE=SHAPE*(Q/(2.0*QLO))**2                                 26H
            ZUP=ZUPP                                                     26I
            K1=1                                                         26J
         22 CONTINUE
            M=N+1
            DO 25 I=1,M                                                  28
            IF(ELORIF.GE.H(I).OR.K.NE.1)GOTO24                           29
            ZUP=H(I)-ELORIF                                              30
            PROD=DELRU(I)*SHAPE*ZUP**3*W**2                              31
            IF (PROD .GT. FACTOR) GO TO 26
            IF(I.EQ.M)GOTO30                                             32
            GO TO 25                                                     32A
         26 RHO=R(I)                                                     32B
            DO 40 J=1,100                                                33
            RHO=RHO+ (R(I-1)-R(I))*0.01                                  34
            ZUP=ZUP-0.01*(H(I)-H(I-1))                                   35
            DELR=RORIF-RHO                                               36
            PROD=DELR*SHAPE*ZUP**3*W**2                                  37
            IF (PROD .LT. FACTOR) GO TO 30                               37A
         40 CONTINUE                                                     37B
            IF (PROD .LT. FACTOR) GO TO 81                               37C
            RHO=R(I-1)                                                   37D
            DO 41 J=1,100                                                37E
            RHO=RHO+(R(I-2)-R(I-1))*0.01                                 37F
            ZUP=ZUP-0.01*(H(I-1)-H(I-2))                                 37G
            DELR=RORIF-RHO                                               37H
            PROD=DELR*SHAPE*ZUP**3*W**2                                  37I
            IF (PROD .LT. FACTOR) GO TO 30                               37J
         41 CONTINUE                                                     38
         24 IF (K .GT. 0) GO TO 25
            IF(H(I).LE.ELORIF)GOTO27
            RHO=RORIF
            ZLO=0.
            DO95 J=1,100
            RHO=RHO+(R(I-1)-RORIF)*0.01
            ZLO=ZLO+0.01*(ELORIF-H(I-1))
            DELR=RHO-RORIF
            PROD=DELR*SHAPE*ZLO**3*W**2
            IF(PROD.GT.FACTOR)GOTO90
         95 CONTINUE
         27 ZLO=ELORIF-H(I)                                              40
            PROD=DELRL(I)*SHAPE*ZLO**3*W**2                              41
            IF (PROD .LT. FACTOR) GO TO 28
```

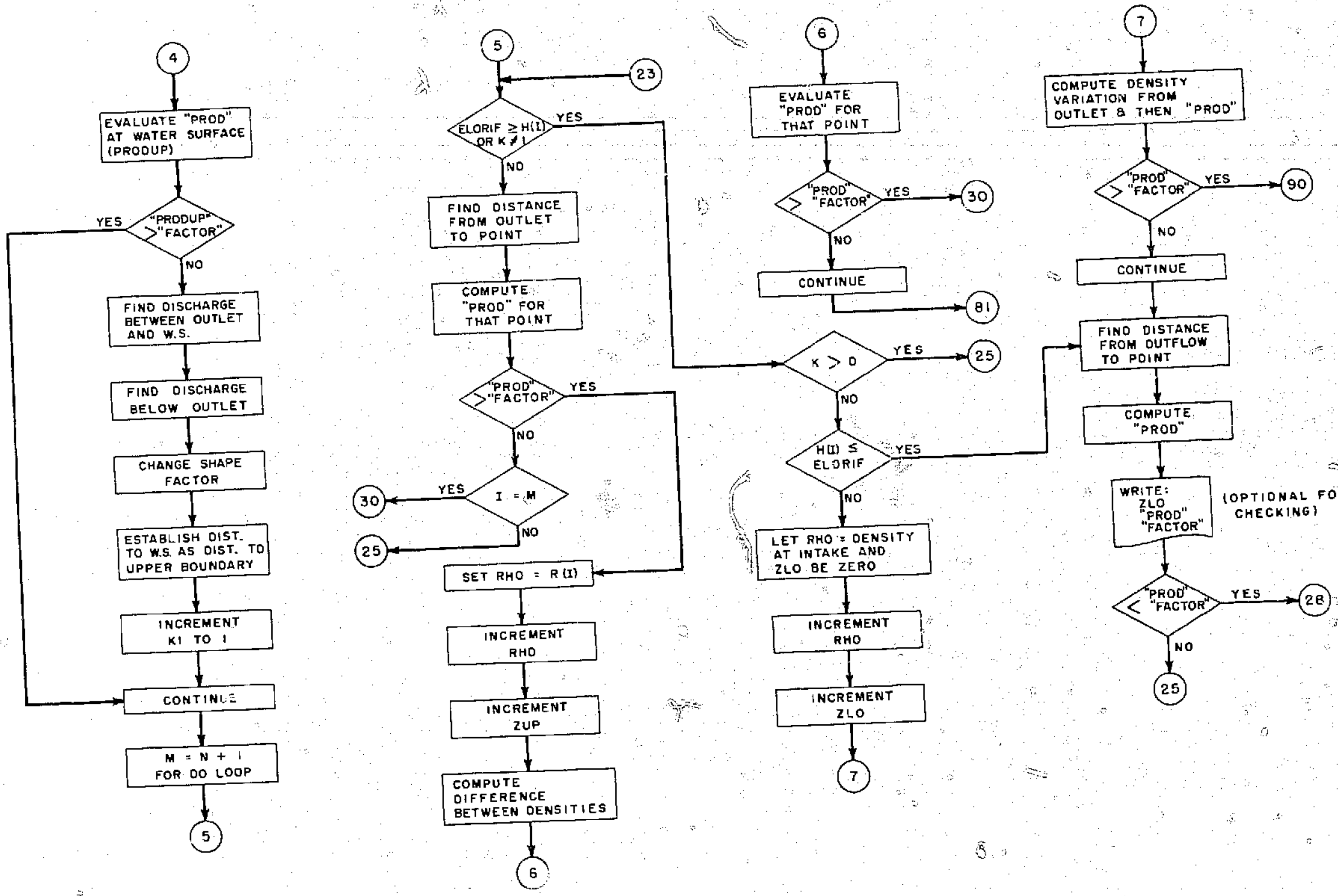
```
      GO TO 25                                                     42
   28 IF (I .EQ. 1) GO TO 29                                       42A
      RHO=R(I)                                                     42B
      DO 80 J=1,100                                                42C
      RHO=RHO+ (R(I-1)-R(I))*0.01                                  43
      ZLO=ZLO+0.01*(H(I)-H(I-1))                                   44
      DELR=RHO-RORIF                                               45
      PROD=DELR*SHAPE*ZLO**3*W**2                                  46
      IF(PROD  .GT.FACTOR)GOTO90                                   47
   80 CONTINUE                                                     48
   81 WRITE (3,82)                                                 48A
      GO TO 30                                                     48B
   82 FORMAT (22H DO LOOP LIMIT REACHED)                           48C
   90 IF(K1)29,29,30                                               48D
   29 K=1                                                          49
      QLO=(Q*PROD/FACTOR)/2.0
      QUP=Q-QLO
      SHAPE=SHAPE*(Q/(2.0*QUP))**2                                 49C
   25 CONTINUE                                                     50
   30 ELUP=ELORIF+ZUP                                              51
      ELLO=ELORIF-ZLO                                              52
      WRITE (3,61) D,Q                                             82A
   61 FORMAT (1H0,13H OUTLET SIZE=,F8.3,11H DISCHARGE=,F8.5)       82B
      WRITE (3,60) ELORIF,ELUP,ELLO                                83
  600FORMAT (13H OUTLET ELEV=,F8.2,13H UPPER LIMIT=,F8.2,13H LOWER LIMI 84
     1T=,F8.2)                                                     85
      GO TO 50                                                     87
   66 END                                                          88
```

APPENDIX D

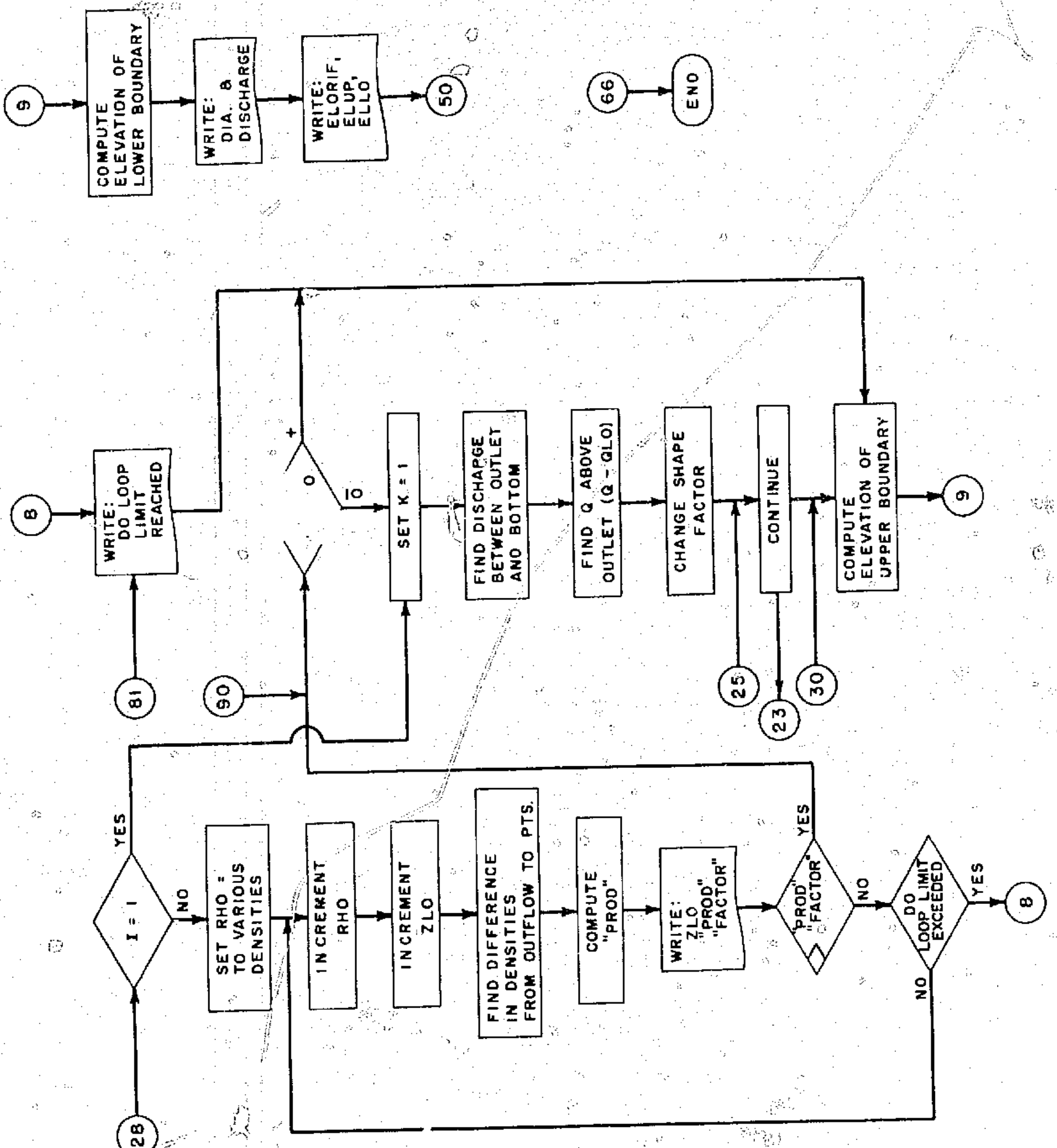
THE FOLLOWING IS A FLOW CHART OF THE SUBJECT PROGRAM.


START
READ TEMP & DENSITY TABLE
READ CORRECTIONS
50
READ N, W, D, WS, BOT, SHAPE,
IF W = 0
YES
66
NO
READ TEMP & ELEVATION
MAKE TEMP CORRECTIONS
IF TEMP > 31
YES
66
NO
TEMP < 0
YES
66
NO
INTERPOLATE FOR DENSITIES
1
1
WRITE OUTPUT HEADING
WRITE: ELEV, TEMP, DENSITY
SHAPE =
NO
WRITE CIRCULAR OUTLET
YES
WRITE SQUARE OUTLET
2
2
READ ELORIF & Q
SET INITIAL VALUE FOR ZUP (ZERO)
SET INITIAL VALUE FOR ZLO (ZERO)
IS OUTLET ABOVE GIVEN POINT
YES
INCREMENT
NO
FIND DENSITY GRADIENT FOR OUTLET INTERVAL
FIND DENSITY AT OUTLET
FIND AREA OF OUTLET
FIND VELOCITY IN OUTLET
EVALVATE "FACTOR"
3
3
INITIALIZE K TO ZERO
IS OUTLET ABOVE GIVEN POINT
NO
COMPUTE DENSITY DIFFERENTIAL IN UPPER LAYER
YES
COMPUTE DENSITY DIFFERENTIAL IN LOWER LAYER
UPPER TEMP LEVEL = WATER SURFACE
FIND DENSITY AT WATER SURFACE
COMPUTE DENSITY DIFFERENTIAL BE- TWEEN ORIFICE & WS
INITIALIZE KI TO ZERO
FIND DISTANCE FROM OUTLET TO WATER SUR.
4

SHEET 2 OF 3


4
EVALUATE "PROD" AT WATER SURFACE (PRODUP)
"PRODUP" > "FACTOR"
YES
NO
FIND DISCHARGE BETWEEN OUTLET AND W.S.
FIND DISCHARGE BELOW OUTLET
CHANGE SHAPE FACTOR
ESTABLISH DIST. TO W.S. AS DIST. TO UPPER BOUNDARY
INCREMENT KI TO I
CONTINUE
M = N + I FOR DO LOOP
5
5
23
ELORIF ≥ H(I) OR K ≠ I
YES
NO
FIND DISTANCE FROM OUTLET TO POINT
COMPUTE "PROD" FOR THAT POINT
"PROD" > "FACTOR"
YES
NO
I = M
YES
30
NO
25
SET RHO = R(I)
INCREMENT RHO
INCREMENT ZUP
COMPUTE DIFFERENCE BETWEEN DENSITIES
6
6
EVALUATE "PROD" FOR THAT POINT
"PROD" > "FACTOR"
YES
30
NO
CONTINUE
81
K > 0
YES
25
NO
H(I) ≤ ELORIF
YES
NO
LET RHO = DENSITY AT INTAKE AND ZLO BE ZERO
INCREMENT RHO
INCREMENT ZLO
7
7
COMPUTE DENSITY VARIATION FROM OUTLET & THEN "PROD"
"PROD" > "FACTOR"
YES
90
NO
CONTINUE
FIND DISTANCE FROM OUTFLOW TO POINT
COMPUTE "PROD"
WRITE: ZLO "PROD" "FACTOR"
(OPTIONAL FOR CHECKING)
"PROD" < "FACTOR"
YES
28
NO
25

SHEET 3 OF 3


9
COMPUTE ELEVATION OF LOWER BOUNDARY
WRITE: DIA. & DISCHARGE
WRITE: ELORIF, ELUP, ELLO
50
66
END
8
WRITE: DO LOOP LIMIT REACHED
81
90
+
0
-0
SET K = 1
FIND DISCHARGE BETWEEN OUTLET AND BOTTOM
FIND Q ABOVE OUTLET (Q - QLO)
CHANGE SHAPE FACTOR
CONTINUE
COMPUTE ELEVATION OF UPPER BOUNDARY
9
25
23
30
28
I = 1
YES
NO
SET RHO = TO VARIOUS DENSITIES
INCREMENT RHO
INCREMENT ZLO
FIND DIFFERENCE IN DENSITIES FROM OUTFLOW TO PTS.
COMPUTE "PROD"
WRITE: ZLO "PROD" "FACTOR"
"PROD" "FACTOR"
YES
NO
DO LOOP LIMIT EXCEEDED
YES
NO
8

7-1750 (3-71)
Bureau of Reclamation

CONVERSION FACTORS–BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
LENGTH		
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
AREA		
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4,046.9	Square meters
Acres	*0.0040469	Square kilometers
Square miles	2.58999	Square kilometers
VOLUME		
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
CAPACITY		
Fluid ounces (U.S.)	29.5737	Cubic centimeters
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3,785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*1,233,500	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
Short tons (2,000 lb)	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
Inch-pounds	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	*Centimeter-kilograms per centimeter*
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
Feet per second	*0.3048 (exactly)**	Meters per second
Feet per year	*0.965873×10^{-6}	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles per hour	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	*0.3048	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	*0.028317	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	*0.453592	Kilograms
Pounds	*4.4482	Newtons
Pounds	*4.4482×10^5	Dynes

Table II—Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	*1.35582	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*0.09290	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor) transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	*304.8	Liters per square meter per day
Pound-seconds per square foot (viscosity)	*4.8824	Kilogram second per square meter
Square feet per second (viscosity)	*0.092903	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	*35.3147	Millicuries per cubic meter
Milliamps per square foot	*10.7639	Milliamps per square meter
Gallons per square yard	*4.527219	Liters per square meter
Pounds per inch	*0.17858	*Kilograms per centimeter*

GPO 854-215

ABSTRACT

Selective outlet works provide an important means by which the quality of water withdrawn from reservoirs may be controlled. This is the third and final report in a series and is part of a continuing effort to develop accurate practicable design and operating criteria for such outlets. The studies discussed here refine previously developed analyses, including evaluation of previous simplifying assumptions, such as a linear density gradient and equal half-layer discharges. A method is presented for predicting velocity distributions within a withdrawal layer. Layers restricted by either the water surface or reservoir bottom and unrestricted layers are considered. The method is compared with experimental and prototype data. Step-by-step design procedures are included.

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Bur Reclam Rep REC-ERC-74-1, Div Gen Res, Jan 1974. Bureau of Reclamation, Denver, 41 p, 7 fig, 2 tab, 7 ref, append

DESCRIPTORS–/ applied research/ reservoirs/ *hydraulic models/ density currents/ hydraulics/ water quality/ temperature/ Froude number/ *stratification/ velocity distribution/ *thermal stratification/ design criteria/ *stratified flow/ *multilevel outlets/ *selective level releases

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