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APPROXIMATE METHOD FOR COMPUTING BACKWATER PROFILES IN CORRUGATED METAL PIPES

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Final Report

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16. Abstract

The determination of the shape and characteristics of a backwater profile in a closed conduit is generally a lengthy and tedious procedure without the use of a computer. Utilizing the charts and tables of this publication and a few simple calculations, it is possible to completely define an M2 profile in a circular structural plate corrugated metal pipe with 6 x 2 inch corrugations. The depth of flow, velocity head, and specific head may be determined at various points along the backwater curve, and the total length of the backwater curve may be defined. Use of the publication will also provide the user with a better understanding of the effects of flow parameter variations on the shape and extent of the backwater profile.

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The Hydraulic Research Group of the Federal Highway Administration began this work in 1969 under the direction of Mr. Herbert G. Bossy, Group Leader, now retired. Initially, the work was performed by Mr. Jerome M. Normann and myself, but circumstances soon separated us, and I continued the research alone. However, Mr. Normann left his contribution in the idea of Diagram No. 1, and later in his review of the whole text. In addition, a great deal of computer assistance was rendered by Mr. James S. Jones, Dr. Ahmed Abdul-Razaq, and Mr. Mario Marques, all of whom were then employed by the Federal Highway Administration.

Their help greatly contributed to the completion of this publication.

Paul N. Zelensky

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LIST OF SYMBOLS

A = Area of flow, square feet

D = Diameter of pipe, feet

d = Depth of flow, feet

d_c = Critical depth, feet

d_{ff} = Depth at full flow, feet

d_n = Normal depth, feet

f = Darcy resistance factor

F_f = Resistance computation factor in terms of Darcy's f

F_{ff} = Resistance computation factor at full flow

g = Gravitational acceleration = 32.16 ft/second^2

H = Specific head = $d + \frac{V^2}{2g}$, or total energy measured above the pipe invert, feet

H_c = Specific head at critical flow, feet

h_f = Friction head loss, feet

H_{ff} = Specific head at full flow, feet

H_n = Specific head at normal depth flow, feet

H_l = Specific head at incremental length of backwater curve $\frac{l}{D}$

H_u = Specific head at the upstream point where the backwater curve terminates, regardless of whether full or uniform flow exists further upstream.

HW = Headwater depth at culvert inlet

L = Length of backwater curve, feet

L_n = Length of normal depth backwater curve, feet

LIST OF SYMBOLS
(CONTINUED)

L_1 = Length of conduit flowing full upstream of backwater curve, feet

l = Incremental length of backwater curve in terms of D. Includes 10, 20, 30, 40, 50, 60, 100 and 200 times D.

HL = Head-Length factor, ranges from 0.1 to 1.0

Q = Discharge, cubic feet/second

R = Hydraulic radius, feet

S_o = Conduit invert slope, feet/foot

S_f = Resistance (friction) slope, slope of total head line, feet/foot

S_{ff} = Resistance slope at full flow, feet/foot

S_{fn} = Resistance slope at normal depth flow, feet/foot

TW = Tailwater depth at culvert outlet

V = Mean velocity of flow = $\frac{Q}{A}$, feet/second

V_c = Critical velocity, feet/second

α = Kinetic energy correction factor = 1.12 for corrugated metal pipes

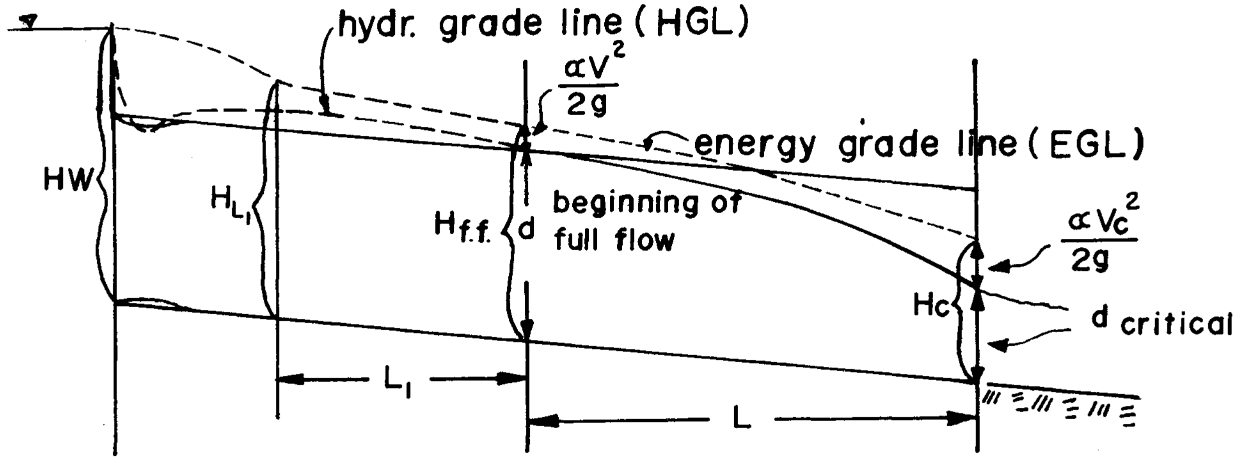
INTRODUCTION

Corrugated metal pipes are often used in the construction of highways as drainage structures, such as culverts and storm drains, and in the fabrication of other hydraulic systems. Structural plate corrugated metal pipes are a very common type of conduit due to the comparative simplicity of their delivery and assembly. This pipe is especially convenient where there is a need for large conduit sizes. However, the large corrugations cause a high hydraulic flow resistance. Thus, where flow conditions are suitable, a well defined backwater curve forms in the pipe.

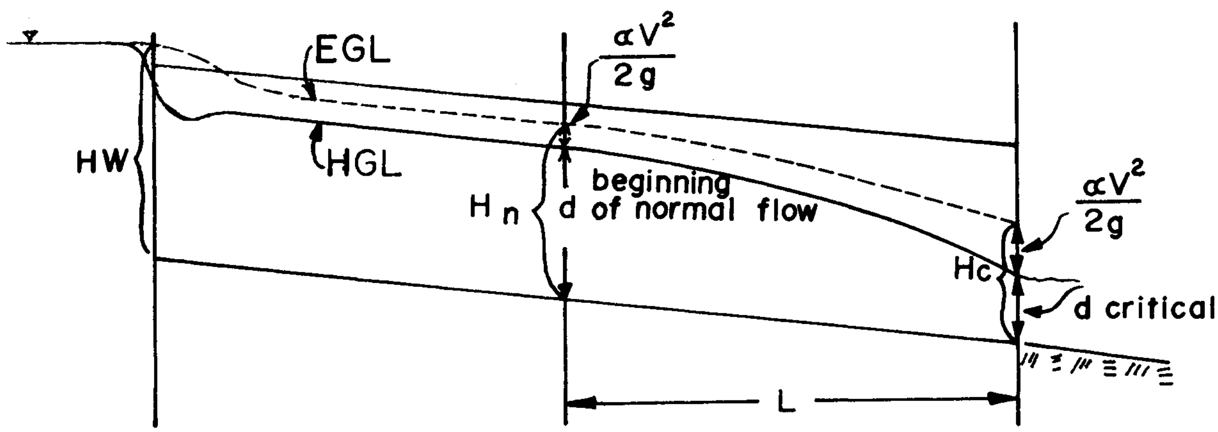
A particular type of subcritical backwater curve which is denoted M2 in hydraulic textbooks will be the subject of this study. The flow conditions which cause this type of backwater curve exist when a long conduit on a mild slope abruptly terminates and the flow undergoes a sudden expansion into the enlarged channel cross section. In the downstream portion of the conduit, a nonuniform, accelerating flow occurs. It passes through critical depth near the controlling point at the pipe outlet where the flow changes from subcritical to supercritical. Tracing the water surface profile from that point upstream a rising curve to the pipe inlet is formed. This is the Type M2 backwater curve.

The length of a backwater curve from the pipe outlet to its upstream terminus depends on basic flow factors such as pipe diameter, D, discharge, Q, conduit invert slope, S_o, and the pipe resistance factor, f. Two types of M2 backwater curves can be distinguished in pipes or closed conduits. The first is when, at some distance upstream, the water surface profile reaches the top of the conduit. From that point upstream, full flow exists in the pipe. The second type of M2 forms when the water surface profile does not reach the top of the conduit but approaches normal depth. In this case, the water surface further upstream is parallel to the conduit invert, maintaining free surface, uniform flow. In the following discussion, the first type of M2 profile will be denoted as a <u>full flow backwater curve</u> and the second type as a <u>normal depth backwater curve</u> (see sketches (a) and (b) below).

Given D, Q, S_o and f, the length, hydraulic gradient and specific head lines of the backwater profile can be computed by one of the conventional hydraulic methods. In the development of the Approximate Method, the Step Method for backwater computation was used (12). A detailed illustration of application of the Step Method can be found in the FHWA publication "Computation of Uniform and Nonuniform Flow in Prismatic Conduits," by Paul N. Zelensky (14).



(a) FULL FLOW BACKWATER CURVE



(b) NORMAL DEPTH BACKWATER CURVE

However, the computation of a backwater profile in a circular pipe is a long and tedious process. This is especially true in the field when no computer is available and several profiles must be computed during the course of a design. The Approximate Method developed in this paper provides a quick and simple solution for determining backwater flow characteristics for any variation of the basic flow parameters over their common ranges. In addition to the determination of specific profiles, insight into the general characteristics of backwater profiles and the effects of variations of basic parameters will be gained.

During the development of the Approximate Method, about 4000 backwater profiles were computed in order to achieve the greatest possible accuracy in an approximate solution.

To generalize the terms, the conventional non-dimensional forms are used in this method. For example, flow depth, cross sectional area, velocity head, and flow are expressed as ratios of pipe diameter, as follows:

Flow depth = $\frac{d}{D}$

Cross sectional area = $\frac{A}{D^2}$

Velocity head = $\frac{\alpha V^2}{2gD}$

Discharge = $\frac{Q}{D^{5/2}}$

Note that the Discharge factor is semi-dimensionless. It is truly dimensionless when divided by $g^{1/2}$, which is assumed to be constant.

SCOPE

A large variety of structural plate corrugated metal pipes with 6 x 2 inch corrugations are manufactured, ranging in size from a diameter of 5.0 ft. to a diameter of 21.0 ft. in increments of 0.5 ft. All basic dimensional data for this pipe are taken from the "Handbook of Steel Drainage and Highway Construction Products," by the American Iron and Steel Institute (6), and supplementary information provided by the Institute. Table 1, Appendix A gives all the available pipe diameters.

The computations in this study were based on nominal pipe diameters to allow for flexibility in the application of this method to other similar conduits with actual dimensions slightly different from those given. The differences between the nominal and the actual dimensions of this pipe are insignificant, so that the maximum possible error will not exceed 5 percent in the horizontal ($\frac{L}{D}$) and 1 percent in the vertical ($\frac{d}{D}$ and $\frac{H}{D}$) computations. This is quite satisfactory for the solution of practical problems.

The ranges of basic hydraulic parameters used in this study are the most common found in drainage engineering practice. The range of the discharge factor is from $\frac{Q}{D^{5/2}} = 0.8$ to $\frac{Q}{D^{5/2}} = 3.2$ which gives the minimum $Q = 0.8\ (5.0)^{5/2} = 44.7$ cfs, and the maximum $Q = 3.2\ (21.0)^{5/2} = 6467$ cfs.

The range of conduit invert slope is from $S_o = 0.000$ (horizontal pipe) to $S_o = 0.030$ (3 percent). For steeper slopes, the flow is usually supercritical and the backwater techniques of this paper no longer apply.

The range of relative flow depths is from $\frac{d}{D} = 0.30$ to $\frac{d}{D} = 1.00$ (full flow).

The approximate results for lower ranges of $\frac{Q}{D^{5/2}}$, and $(\frac{L}{D})_n$ deviate from the true solutions. The lower the parameters, the more unsteady and less reliable the solutions become.

The kinetic energy correction factor, α, was taken to be 1.12, which has been determined appropriate based on velocity distribution measurements in pipes with 6 x 2 inch corrugations.

FLOW RESISTANCE FACTORS

To compute a backwater profile for a certain type of conduit, the Darcy resistance factor, f, resistance computation factor, F_f, and the resistance slope, S_f, should be known. Using Darcy's equation:

$$h_f = f \frac{L}{D} \frac{V^2}{2g}$$

in which h_f is the head loss due to frictional resistance, ft.

f is the resistance factor

L is the length of the conduit, ft.

D is the pipe diameter, ft.

V is the flow velocity, fps,

g is gravitational acceleration = 32.16 ft./sec.^{2}

Rearranging, the resistance slope is:

$$\frac{h_f}{L} = S_f = \frac{f}{D} \frac{V^2}{2g} = \frac{f}{4R} \frac{V^2}{2g} = \frac{f}{2g} \left(\frac{0.25Q^2}{\frac{RA^2}{D^5} D^5} \right)$$

$$S_f = \frac{f}{2g} \frac{0.25}{\left(\frac{A}{D^2}\right)^2 \left(\frac{R}{D}\right)} \left(\frac{Q}{D^{5/2}}\right)^2 =$$

$$= 0.003887\ f \frac{1}{\left(\frac{A}{D^2}\right)^2 \left(\frac{R}{D}\right)} \left(\frac{Q}{D^{5/2}}\right)^2$$

in which Q is the discharge

A is the area of the flow prism

R is the hydraulic radius of the flow prism, and

D = 4R for full circular pipes.

As a result of an analysis of laboratory data by Mr. H. G. Bossy in 1968, the resistance factor, f, for corrugated metal pipe with 6 x 2 inch corrugations, including minor losses due to bolts, was found to be:

$$f = \frac{0.253}{D^{0.474}}$$

Setting D = 4R

$$f = \frac{0.253}{1.929\ R^{0.474}} = \frac{0.13114}{R^{0.474}}$$

Therefore,

$$S_f = 0.003887 \times 0.13114 \frac{1}{R^{0.474} \left(\frac{A}{D^2}\right)^2 \left(\frac{R}{D}\right)} \left(\frac{Q}{D^{5/2}}\right)^2 =$$

$$= \frac{0.0005098}{\left(\frac{A}{D^2}\right)^2 \left(\frac{R}{D}\right)^{1.474} D^{0.474}} \left(\frac{Q}{D^{5/2}}\right)^2$$

Setting

$$F_f = \frac{0.005098}{\left(\frac{A}{D^2}\right)^2 \left(\frac{R}{D}\right)^{1.474}}$$

then

$$S_f = F_f \frac{1}{D^{0.474}} \left(\frac{Q}{D^{5/2}}\right)^2$$

in terms of Darcy's f. F_f is the resistance computation factor for this particular type of corrugated metal pipe. Table 1, Appendix A, of this publication gives $D^{0.475}$ and $D^{2.5}$ values for all available circular pipe diameters. Tabulated values of F_f are given in Table 2, for various depths of flow in circular 6 x 2 inch structural plate corrugated metal pipes.

BACKWATER FLOW IN PIPE

A series of discharge curves with the coordinates $\frac{H}{D}$ versus $S_oD^{0.474}$ are presented in Figure 1. The parameters of the curves are $\frac{d}{D}$ and $\frac{Q}{D^{5/2}}$. The right edge represents critical flow (minimum specific head, $\frac{H}{D}$, for a given flow rate, $\frac{Q}{D^{5/2}}$).

Assuming that D, Q, and S_o are known, the curves of Figure 1 are used to determine which type of flow exists in a pipe and to find the two extreme specific head values for a backwater condition. One is at critical depth at the pipe outlet and the other at the upstream end of the backwater profile, where full flow or normal depth flow begins.

In determining the type of flow, one of three cases may result. (a) If a vertical line drawn from $S_o\ D^{0.474}$ falls to the right of the critical flow point on the corresponding $\frac{Q}{D^{2/5}}$ curve, it means that the flow in the pipe is supercritical and there is no M2 backwater curve. (b) If a vertical from $S_o\ D^{0.474}$ intersects the appropriate $\frac{Q}{D^{5/2}}$ curve, it means that the flow in the pipe is subcritical and the backwater curve transitions from critical depth at the pipe outlet to the point where normal depth begins. (c) If a vertical from $S_o\ D^{0.474}$ passes to the left of the appropriate $\frac{Q}{D^{5/2}}$ curve, the subcritical backwater curve connects critical depth at the pipe outlet with full flow at the upstream end. Note that the leftmost point on the $\frac{Q}{D^{5/2}}$ curves is where the curves intersect $\frac{d}{D} = 0.935$.

In cases where the vertical from $S_oD^{0.474}$ is tangent to the $\frac{Q}{D^{5/2}}$ curve, the flow conditions fluctuate between normal depth and full flow and is considered to be full flow, since any slight increase in resistance (such as a discontinuity in the pipe) will throw the flow into a full flow condition.

Because of this instability in determining the flow type in the pipe, the upper portion of the $\frac{Q}{D^{5/2}}$ curves from the point of their intersections with the $\frac{d}{D}$ = 0.935 line to the point of their intersection with the full flow line should not be considered. The purpose of the line $\frac{d}{D}$ = 0.935 is to point out the leftmost point on each $\frac{Q}{D^{5/2}}$ curve. That is the transition point where normal depth flow changes to full flow for all $S_oD^{0.474}$ values lying to its left.

The purpose of the full flow line in the graph is to show the specific head value $\frac{H}{D}$ at full flow for each of the $\frac{Q}{D^{5/2}}$ curves. These values are found at the points where the $\frac{Q}{D^{5/2}}$ curves terminate on the full flow line, and represent the condition where the Hydraulic Grade Line touches the top of the pipe.

However, the specific head values for normal depth backwater curves are found at the intersection of the vertical from $S_oD^{0.474}$ with the corresponding $\frac{Q}{D^{5/2}}$ curve.

The $\frac{d}{D}$ values for any values of $\frac{H}{D}$ can be found by the interpolating between $\frac{d}{D}$ lines.

Two examples of determining the type of flow in a pipe and the specific head values follow:

<u>EXAMPLE 1</u>:

Given: D = 13.0 ft; Q = 975 cfs; S_o = 0.004

From Table 1, $13^{5/2}$ = 609.34; $13^{0.474}$ = 3.3729

$$\frac{Q}{D^{5/2}} = \frac{975}{609.34} = 1.6;$$

$$S_o\ D^{0.474} = 0.004 \times 3.3729 = 0.0135$$

Thus, the flow is subcritical. The backwater curve intersects the top of the pipe at some point upstream.

$$\frac{H_c}{D} = 0.776;\quad \frac{d_c}{D} = 0.55;\quad \left(\frac{H}{D}\right)_{ff} = 1.070$$

EXAMPLE 2:

Given: D = 8.0 ft; q = 362 cfs; So = 0.0120

$$\frac{Q}{D^{5/2}} = \frac{362}{181.0} = 2.0$$

$$S_o \; D^{0.474} = 0.0120 \times 2.6796 = 0.0322$$

Again, the flow is subcritical. The backwater curve transitions into a normal depth condition.

$$\frac{H_c}{D} = 0.884; \; \frac{d_c}{D} = 0.62; \; \frac{H_n}{D} = 0.912; \; \frac{d_n}{D} = 0.73$$

BACKWATER CURVE LENGTH

No method has been developed for reducing the backwater length curves ($\frac{L}{D}$ vs. S) to a common diagram combining size D, discharge factor, $\frac{Q}{D^{5/2}}$, and invert slope, S_o.

The $\frac{L}{D}$ function is apparently unamenable to such a generalization. Separate diagrams for neighboring pipe sizes, D, have some similarity, however. Therefore, one diagram can be used for several sizes with an acceptable degree of accuracy. A list, grouping all 33 sizes into 11 figures for backwater curve length is presented at the end of this chapter. For the worst case, the error in $\frac{L}{D}$ does not exceed 20 percent. If a higher degree of accuracy is needed, an interpolation between two figures should be performed. The $\frac{L}{D}$ diagram for a given size D consists of a series of $\frac{L}{D}$ curves with coordinates $\frac{L}{D}$ and S_o. For each value of $\frac{Q}{D^{5/2}}$ there are two $\frac{L}{D}$ curves. One is for full flow backwater curves and another is for normal depth backwater curves.

When increasing the slope of the conduit invert from S_o = 0.000 for a full flow condition, the point where the backwater curve reaches the top of the conduit moves upstream and the backwater curve length, $\frac{L}{D}$, increases. At a certain value of slope, S_o, the backwater curve no longer reaches the top of the conduit, but the conditions leading to normal depth in the pipe occur and the backwater curve reaches normal depth, $\frac{d_n}{D}$. By further increasing the invert slope, the backwater curve becomes shorter until the slope reaches its critical value.

The value of the invert slope transitional between full flow and normal depth flow is determined solely by the magnitudes of D and Q. In the Figures 2 - 12, at their maximum $\frac{L}{D}$, both curves approach a vertical asymptote which is the transitional slope between the two types of flow.

To find the value of the transitional slope between full flow and normal depth backwater curves for any value of D and Q, the minimum value of the resistance computation factor, F_f, for $\frac{d}{D} = 0.935$, can be inserted in the equation:

$$S_f = \frac{F_f}{D^{0.479}} \left(\frac{Q}{D^{5/2}}\right)^2$$

resulting in:

$$S_f = \frac{0.005395}{D^{0.474}} \left(\frac{Q}{D^{5/2}}\right)^2$$

The tabulated values of transitional invert slopes for all 33 pipe sizes are given in Appendix A, Table 3.

It should be kept in mind that sometimes the backwater curve can be very long, actually longer than the conduit. Then, the backwater profile can be traced upstream as far as the conduit inlet. The flow regime upstream of the pipe is, of course, different than the regime within the pipe.

The backwater curve is very sensitive to the flow conditions. Any slight change of these conditions can affect the length of the curve. Short normal depth backwater curves are especially unstable. Their lengths are very approximate. Therefore, the portions of the curves with $\frac{L}{D}$ values less than ten are not included in the diagrams.

An interpolation between two neighboring diagrams for a more precise determination of the backwater curve length is simple if the backwater flow curves in both diagrams are of the same type; that is, either full flow or normal depth flow. Then, the desired value is not an arithmetic mean but can be determined as follows: the two values of $\frac{L}{D}$ found from two different diagrams must be marked on the appropriate $\frac{Q}{D^{5/2}}$ curve. The desired $\frac{L}{D}$ value is the midpoint between the two values. If, however, the flow curves in the neighboring diagrams are of different flow types, the type of the desired flow curve should be found from Table 3. Then one known value, $\frac{L}{D}$, of the same type of flow should be marked on the appropriate curve and the sought value of $\frac{L}{D}$ has to be estimated using engineering judgement, taking into consideration that as the value approaches the vertical asymptote, it becomes less reliable.

EXAMPLE 3:

Given: $D = 17.0$ ft; $Q = 2145$ cfs; $\frac{Q}{D^{5/2}} = 1.8$; $S_o = 0.004$;

Find $\frac{L}{D}$.

Interpolation will be performed using two figures: Fig. 10 (D = 16.0 ft) and Fig. 11 (D = 18.0 ft). Fig. 10: $\frac{L}{D} = 210$, at full flow; Fig. 11: $\frac{L}{D} = 330$, at full flow. The midpoint between $\frac{L}{D} = 210$ and 330 is 260. The actual value of $\frac{L}{D}$, computed for D = 17.0 ft. is 255. So, the error is two percent.

A similar procedure is used for normal depth curves.

EXAMPLE 4:

Given: $D = 17.0$ ft; $Q = 2383$ cfs; $\frac{Q}{D^{5/2}} = 2.0$; $S_o = 0.006$;

Find $\frac{L}{D}$.

Fig. 10: $\frac{L}{D} = 410$, at normal depth flow; Fig. 11: $\frac{L}{D} = 255$, at normal depth flow. The midpoint on the normal depth flow curve is $\frac{L}{D} = 320$. The actual $\frac{L}{D}$ value, computed for D = 17.0 ft: $\frac{L}{D} = 290$. So, the error is ten percent.

EXAMPLE 5:

Given: $D = 17.0$ ft; $Q = 1430$ cfs; $\frac{Q}{D^{5/2}} = 1.2$; $S_o = 0.002$;

Find $\frac{L}{D}$.

Fig. 10: $\frac{L}{D} = 1100$, at full flow; Fig. 11: $\frac{L}{D} = 1100$, at normal depth flow. From Table 3, the $\frac{L}{D}$ value sought is on the full flow curve. It should be higher than 1100. Let us assume $\frac{L}{D} = 1200$. The actual $\frac{L}{D}$ value computed for D = 17.0 ft: $\frac{L}{D} = 1400$. So, the error is 14 percent.

LIST OF PIPE SIZES
WITH SIMILAR $\frac{L}{D}$ VS. S_o CURVES

Fig. No.	Diameter Group in Feet
2	*5.0*
3	5.5, *6.0*
4	6.5, *7.0*
5	7.5, *8.0*
6	8.5, *9.0*
7	9.5, *10.0*, 10.5
8	11.0, 11.5, *12.0*, 12.5
9	13.0, 13.5, *14.0*, 14.5
10	15.0, 15.5, *16.0*, 16.5
11	17.0, 17.5, *18.0*, 18.5
12	19.0, 19.5, *20.0*, 20.5, 21.0

HL FACTOR CURVES

The Head Length factor, HL, was developed to provide a quick and relatively accurate means of determining intermediate specific head values, $\frac{H_l}{D}$, lying between the beginning of the end of a backwater curve. The computed intervals are $\frac{l}{D}$ = 10, 20, 30, 40, 50, 60, 100, and 200. The HL factor curves for these values of $\frac{l}{D}$ are plotted with the coordinates HL versus length of backwater curve $\frac{L}{D}$ in Fig. 13 for full flow backwater curves and in Fig. 14 for normal depth backwater curves.

The curve for each value of $\frac{l}{D}$ was developed as the mean obtained by numerous variations of D, $\frac{Q}{D^{5/2}}$, S_o, and $\frac{L}{D}$. From research, the following relation was found:

$$HL = \frac{\frac{H_l}{D} - \frac{H_c}{D}}{\frac{H_u}{D} - \frac{H_c}{D}}$$

in which: HL = Head-Length factor.

$\frac{H_l}{D}$ = specific head at a distance $\frac{l}{D}$ upstream from critical depth.

$\frac{H_c}{D}$ = specific head at critical depth

$\frac{H_u}{D}$ = specific head at the upstream end of the backwater curve.

The HL factor for the definite incremental length, $\frac{l}{D}$, of the backwater curve may be found from Fig. 13 or 14 using the total backwater curve length, $\frac{L}{D}$. Then, $\frac{H_l}{D}$ may be determined as follows:

$$\frac{H_l}{D} = HL\left(\frac{H_u}{D} - \frac{H_c}{D}\right) + \frac{H_c}{D}$$

which is true for any of the forementioned values of $\frac{l}{D}$.

DESIGN PROCEDURE

To find the type of backwater curve in the pipe and determine its profile by the Approximate Method when D, Q, and S_o are given, the following procedure should be followed:

1. From Table 1, find values for $D^{5/2}$, $D^{0.474}$, and compute the factors $\frac{Q}{D^{5/2}}$ and $S_o\ D^{0.474}$.

2. From Fig. 1, find the type of flow, type of backwater curve, and relative depth and specific head values for the beginning and the end points of the backwater curve.

3. From Figs. 2 through 12, find length of the backwater curve $\frac{L}{D}$.

4. From Fig. 13 or 14 find HL factors for all desired $\frac{l}{D}$ values.

5. Using the equation for $\frac{H_l}{D}$, find $\frac{H_l}{D}$ for all the intermediate points on the backwater curve.

6. From Fig. 1, find depths $\frac{d}{D}$ for the all intermediate points by interpolating $\frac{H_l}{D}$ values between $\frac{d}{D}$ lines.

In case it is necessary to find a specific head value $(\frac{H}{D})_{L_1}$ at some distance $\frac{L_1}{D}$ upstream from the end of a full flow backwater curve, the following computation should be used:

$$\left(\frac{H}{D}\right)_{L_i} = \left(\frac{H}{D}\right)_{ff} + \left(S_{ff} - S_o\right)\frac{L_1}{D}$$

$$S_{ff} = F_{ff}\ \frac{\left(\frac{Q}{D^{5/2}}\right)^2}{D^{0.474}} = 0.006374\ \text{(Table 2)}\ \frac{\left(\frac{Q}{D^{5/2}}\right)^2}{D^{0.474}}$$

$$\left(\frac{H}{D}\right)_{L_1} = \left(\frac{H}{D}\right)_{ff} + \left[0.006374\ \frac{\left(\frac{Q}{D^{5/2}}\right)^2}{D^{0.474}} - S_o\right]\frac{L_1}{D}$$

See sketch (a). Full Flow Backwater Profile.

EXAMPLE 6:

Given: $D = 12.0$ ft; $Q = 600$ cfs; $S_o = 0.003$

From Table 2, $D^{5/2} = 4.99$; $D^{0.474} = 3.247$; $\frac{Q}{D^{5/2}} = 1.2$;

$S_o\ D^{0.474} = 0.0097$;

From Fig. 1, the flow approaches normal depth, and

$\frac{d_c}{D} = 0.48$; $\frac{H_c}{D} = 0.66$; $\frac{d_n}{D} = 0.78$; $\frac{H_n}{D} = 0.834$;

$\frac{L}{D}$ from Fig. 8 = 460; $\frac{H_n}{D} - \frac{H_c}{D} = 0.174$

$$\frac{H_l}{D} = HL\ \left(\frac{H_u}{D} - \frac{H_c}{D}\right) + \frac{H_c}{D} = HL\ \left(\frac{H_n}{D} - \frac{H_c}{D}\right) + \frac{H_c}{D}$$

for a normal depth backwater curve.

$\frac{l}{D}$	Approx. method Fig. 14		Actual Computed	Error	Approx. meth. and actual Fig. 1
	HL	$\frac{H_l}{D}$	$\frac{H_l}{D}$	%	$\frac{d}{D}$
10	0.265	0.706	0.706	0.0	0.60
20	0.395	0.729	0.731	0.3	0.65
30	0.485	0.744	0.748	0.5	0.66
40	0.565	0.758	0.761	0.4	0.68
50	0.620	0.768	0.772	0.5	0.70
60	0.670	0.777	0.781	0.5	0.71
100	0.785	0.797	0.804	0.9	0.73
200	0.924	0.821	0.828	0.8	0.77

Assume, that from Hydraulic Engineering Circulars No. 5 and 13, (3, 4) the following culvert has been selected, operating in outlet control:

$D = 12$ ft; $Q = 600$ cfs; $S_o = 0.003$;

Elevation outlet invert = 200.0 ft.

Elevation inlet invert = 201.5 ft.

Length = 500 ft.

Conduit is a circular structural plate corrugated metal pipe, with 6 x 2 inch corrugations.

Entrance - projecting with entrance loss coefficient k_e = .09.

From HEC 5 and 13 it is found that the headwater pool elevation is 210.8, or 9.3 ft. above the inlet invert. It is desired to check this result more exactly, using the method described herein.

From Example 6, at the pipe outlet:

$$\frac{d_c}{D} = 0.48; \; d_c = 5.76 \text{ ft.}; \; \frac{H_c}{D} = 0.66; \; H_c = 7.92 \text{ ft.}$$

$$\frac{\alpha V_c^{\,2}}{2gD} = 0.66 - 0.48 = 0.18; \; \frac{\alpha V_c^{\,2}}{2g} = 2.16 \text{ ft.}$$

at the upstream end of the pipe:

$$\frac{l}{D} = \frac{500}{12} = 41.7$$

at $\frac{l}{D} = 41.7$, by interpolation, HL = 0.58

$$\frac{H_l}{D} = 0.58 \quad (0.174) + 0.66 = 0.76$$

From Fig. 1, $\frac{d}{D} = 0.685$

$$\frac{\alpha V^2}{2gD} = 0.76 - 0.685 = 0.075$$

$$\frac{\text{Inlet Losses}}{D} = \frac{k_e}{\alpha}\left(\frac{\alpha V^2}{2gD}\right) = \frac{0.9}{1.12}(0.075) = 0.060$$

Thus, the inlet pool elevation is:

$$\left[\frac{H_l}{D} + \frac{\text{Inlet Losses}}{D}\right] D + \text{Elev. Inlet Invert} =$$

[0.76 + 0.06] 12.0 + 201.5 = 211.3

Thus, the headwater pool elevation is actually 0.5 feet higher than computed from HEC 5 and 13.

EXAMPLE 7:

In the previous example, only the special case of critical depth at the outlet was considered. In the more general case where there is some tailwater due to backwater in the receiving channel, the solution is similar except that one must begin the computations in an imaginary extension of the culvert. Computations must always begin at critical depth. In the tailwater case, one simply determines where the computed backwater profile matches tailwater at the outlet and uses the upper part of the profile. To illustrate the procedure for handling the tailwater case assume that the following culvert, operating in outlet control has been selected:

$D = 10$ ft; $Q = 600$ cfs; $S_o = 0.002$;

Elevation outlet invert = 100.0 ft.

Elevation inlet invert = 100.8 ft.

Length = 390 ft.

Conduit is a circular structural plate corrugated metal pipe, with 6 x 2 inch corrugations.

Entrance - square edge in a concrete headwall, k_e = 0.5 (from HEC No. 5)

Tailwater depth at the outlet is 0.8 x D. Thus, $\frac{TW}{D} = 0.80$.

From HEC 5 and 13 it is found that headwater pool elevation is 112.1 or 11.2 ft. above the inlet invert. It is desired to check this result using the method developed herein:

$$\frac{Q}{D^{5/2}} = \frac{600}{316.2} = 1.9; \quad S_o D^{0.474} = 0.002 \times 2.979 = 0.00596;$$

From Fig. 1, the flow is full flow and:

$$\frac{d_c}{D} = 0.61; \quad \frac{H_c}{D} = 0.86; \quad \frac{H_{ff}}{D} = 1.10; \quad \left(\frac{V^2}{2gD}\right)_{ff} = 0.100;$$

From Fig. 7, $\frac{L}{D} = 44$

$$\frac{H_{ff}}{D} - \frac{H_c}{D} = 0.24;$$

$$\frac{H_l}{D} = HL \left(\frac{H_{ff}}{D} - \frac{H_c}{D}\right) + \frac{H_c}{D} \text{ for full flow backwater curve.}$$

Using Fig. 13:

$\frac{l}{D}$	HL	$\frac{H_l}{D}$	$\frac{d}{D}$
10	0.32	0.94	0.80
20	0.53	0.99	0.87
30	0.72	1.03	0.93
40	0.92	1.08	0.98

Plot the backwater profile to scale.

Find where the plotted profile matches the tailwater at the outlet (i.e., $\frac{d}{D} = \frac{TW}{D} = 0.80$ in this example); this match point is referred to as Point A hereafter. The actual backwater profile is from Point A up to the point where the water surface profile reaches the top of the conduit.

The length of the actual backwater profile is determined by the plotted profile using only the upper part of the profile after $\frac{d}{D}$ matches the tailwater depth ratio $\frac{TW}{D}$.

$$\left(\frac{L}{D}\right)_{actual} = 44 - 10 = 34$$

Total culvert length is 390 ft., or 39 times D. The length ratio of full flow is:

$$\frac{L_1}{D} = 39 - 34 = 5$$

The headwater pool elevation is:

$$\frac{HW}{D} = \left(\frac{H}{D}\right)_{L_1} + \frac{\text{Inlet Losses}}{D}$$

$$\frac{HW}{D} = \frac{H_{ff}}{D} + (S_{ff} - S_o)\frac{L_1}{D} + \frac{\text{Inlet Losses}}{D}$$

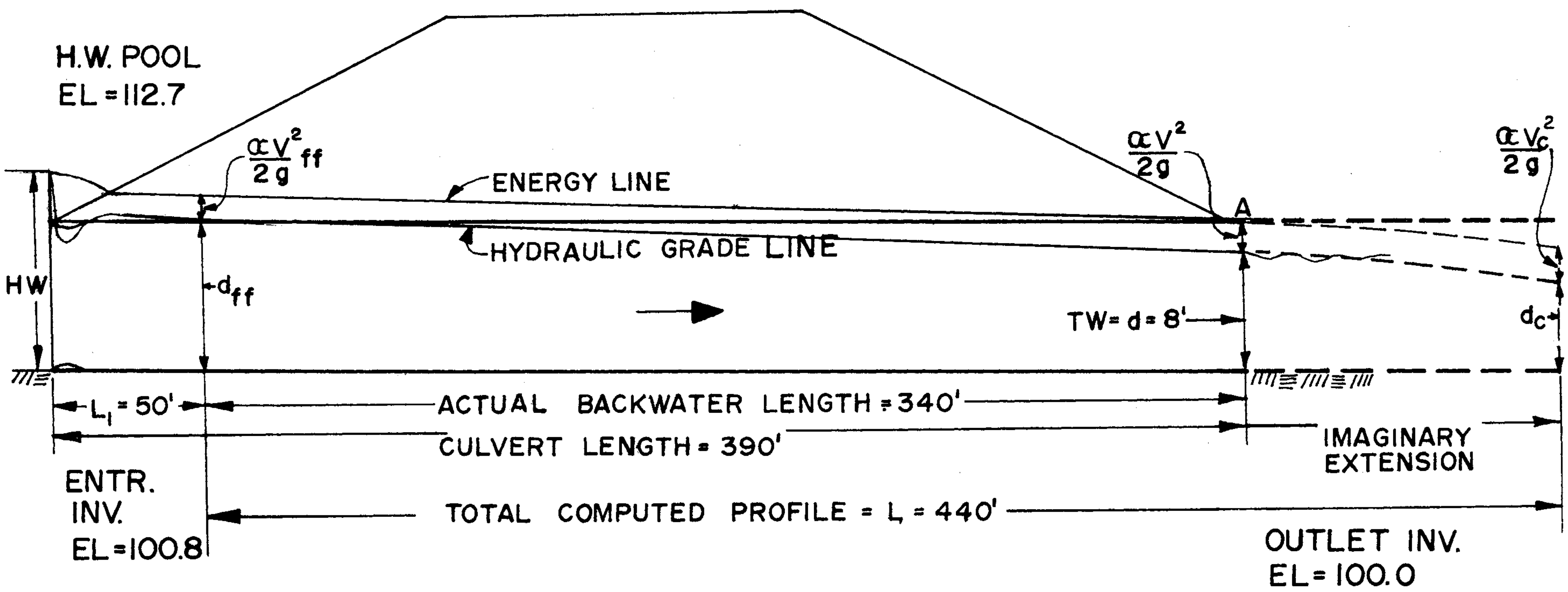
$$\frac{HW}{D} = \frac{H_{ff}}{D} + \left[\left(0.006374 \cdot \frac{\left(\frac{Q}{D^{5/2}}\right)^2}{D^{0.474}}\right) - 0.002\right]\frac{L_1}{D} + \frac{k_e}{\alpha} \cdot \frac{\alpha V^2}{2gD}$$

$$\frac{HW}{D} = 1.10 + \left[0.006374\left(\frac{3.61}{2.979}\right) - 0.002\right] 5 + 0.45\ (0.10)$$

$$\frac{HW}{D} = 1.10 + 0.0286 + 0.045 = 1.1736$$

$$HW = 1.1736 \times 10 = 11.74 \text{ ft.}$$

Headwater pool elevation = 100.8 + 11.74 = 112.5 or 0.5 ft. higher than determined from HEC 5 and 13.



DEFINITIVE SKETCH FOR A CULVERT WITH TAILWATER AT THE OUTLET
(EXAMPLE 7)

APPENDIX A: TABLES & DESIGN FIGURES

Table 1.

$D^{0.474}$ and $D^{2.5}$ value for various diameters

Diameter (ft.)		$D^{0.474}$	$D^{2.5}$	Plates per ring
Nominal	Actual	Nominal	Nominal	
5.0	4.93	2.144	55.90	4
5.5	5.43	2.244	70.94	4
6.0	5.94	2.338	88.18	4
6.5	6.45	2.428	107.7	4
7.0	6.97	2.515	129.6	4
7.5	7.48	2.599	154.0	6
8.0	7.98	2.680	181.0	6
8.5	8.49	2.758	210.6	6
9.0	9.00	2.833	243.0	6
9.5	9.51	2.907	278.2	6
10.0	10.02	2.979	316.2	6
10.5	10.53	3.048	357.3	6
11.0	11.03	3.116	401.3	8
11.5	11.55	3.183	448.5	8
12.0	12.06	3.247	498.8	8
12.5	12.57	3.311	552.4	8
13.0	13.08	3.373	609.3	8

Table 1 (cont'd)

Diameter (ft.)		$D^{0.474}$	$D^{2.5}$	Plates per ring
Nominal	Actual	Nominal	Nominal	
13.5	13.58	3.434	669.6	8
14.0	14.09	3.494	733.4	8
14.5	14.60	3.552	800.6	10
15.0	15.11	3.610	871.4	10
15.5	15.62	3.666	945.9	10
16.0	16.13	3.722	1024	10
16.5	16.64	3.776	1106	10
17.0	17.15	3.830	1192	10
17.5	17.66	3.883	1281	10
18.0	18.17	3.935	1375	12
18.5	18.67	3.987	1472	12
19.0	19.18	4.038	1574	12
19.5	19.69	4.088	1679	12
20.0	20.21	4.137	1789	12
20.5	20.72	4.186	1903	12
21.0	21.22	4.234	2021	12

Table 2.

Resistance computation factor F_f in terms of the Darcy f

$$F_f = \frac{0.0005097}{\left(\frac{A}{D^2}\right)^2 \left(\frac{R}{D}\right)^{1.474}}$$

A = Area of flow
D = Pipe diameter
R = Hydraulic radius

$\frac{d}{D}$	F_f	$\frac{d}{D}$	F_f	$\frac{d}{D}$	F_f
1.00	0.006374	0.84	0.005951	0.67	0.01001
0.99	0.005820	0.83	0.006068	0.66	0.01045
0.98	0.005639	0.82	0.006198	0.65	0.01092
0.97	0.005529	0.81	0.006339	0.64	0.01143
0.96	0.005459	0.80	0.006492	0.63	0.01198
0.95	0.005418	0.79	0.006658	0.62	0.01258
0.94	0.005398	0.78	0.006839	0.61	0.01322
*0.935	0.005395	0.77	0.007033	0.60	0.01392
0.93	0.005396	0.76	0.007243	0.59	0.01468
0.92	0.005410	0.75	0.007468	0.58	0.01550
0.91	0.005437	0.74	0.007711	0.57	0.01640
0.90	0.005476	0.73	0.007973	0.56	0.01737
0.89	0.005528	0.72	0.008254	0.55	0.01844
0.88	0.005590	0.71	0.008557	0.54	0.01960
0.87	0.005664	0.70	0.008882	0.53	0.02088
0.86	0.005749	0.69	0.009232	0.52	0.02228
0.85	0.005844	0.68	0.009609	0.51	0.02381

*Minimum value

Table 2 (cont'd)

$\frac{d}{D}$	F_f	$\frac{d}{D}$	F_f	$\frac{d}{D}$	F_f
0.50	0.02551	0.43	0.04384	0.36	0.08575
0.49	0.02738	0.42	0.04782	0.35	0.09563
0.48	0.02944	0.41	0.05231	0.34	0.10705
0.47	0.03174	0.40	0.05739	0.33	0.12032
0.46	0.03428	0.39	0.06315	0.32	0.13581
0.45	0.03712	0.38	0.06969	0.31	0.15399
0.44	0.04029	0.37	0.07717	0.30	0.17544

Table 3.
Invert slope transitional values

S_f values where $S_f = S_o = \left(\frac{0.005395}{D^{0.474}}\right)\left(\frac{Q}{D^{5/2}}\right)^2$

S_f = Resistance slope
S_o = Invert slope
D = Pipe diameter
Q = Flow discharge

If $S_o >$ transitional slope, backwater curve approaches normal depth.
If $S_o <$ transitional slope, backwater curve approaches full flow.

D	$\frac{Q}{D^{5/2}}$					
	0.8	0.9	1.0	1.1	1.2	1.3
5.0	.00161	.00204	.00252	.00304	.00362	.00425
5.5	.00154	.00195	.00241	.00291	.00346	.00406
6.0	.00148	.00187	.00231	.00279	.00332	.00390
6.5	.00142	.00180	.00222	.00269	.00320	.00376
7.0	.00137	.00174	.00215	.00260	.00309	.00363
7.5	.00133	.00168	.00208	.00251	.00299	.00351
8.0	.00129	.00163	.00201	.00243	.00290	.00340
8.5	.00125	.00158	.00196	.00237	.00282	.00331
9.0	.00122	.00154	.00190	.00230	.00274	.00322
9.5	.00119	.00150	.00186	.00225	.00267	.00314
10.0	.00116	.00147	.00181	.00219	.00261	.00306
10.5	.00113	.00143	.00177	.00214	.00255	.00299
11.0	.00111	.00140	.00173	.00210	.00249	.00293
11.5	.00109	.00137	.00170	.00205	.00244	.00287
12.0	.00106	.00135	.00166	.00201	.00239	.00281
12.5	.00104	.00132	.00163	.00197	.00235	.00275
13.0	.00102	.00130	.00160	.00194	.00230	.00270
13.5	.00101	.00127	.00157	.00190	.00226	.00266
14.0	.00099	.00125	.00154	.00187	.00222	.00261
14.5	.00097	.00123	.00152	.00184	.00219	.00257
15.0	.00096	.00121	.00150	.00181	.00215	.00253
15.5	.00094	.00119	.00147	.00178	.00212	.00249
16.0	.00093	.00117	.00145	.00175	.00209	.00245
16.5	.00091	.00116	.00143	.00173	.00206	.00241
17.0	.00090	.00114	.00141	.00170	.00203	.00238
17.5	.00089	.00113	.00139	.00168	.00200	.00235
18.0	.00088	.00111	.00137	.00166	.00197	.00232
18.5	.00087	.00110	.00135	.00164	.00195	.00229
19.0	.00086	.00108	.00134	.00162	.00192	.00226
19.5	.00085	.00107	.00132	.00160	.00190	.00223
20.0	.00084	.00106	.00130	.00158	.00188	.00220
20.5	.00083	.00104	.00129	.00156	.00186	.00218
21.0	.00082	.00103	.00127	.00154	.00184	.00215

Table 3 (cont'd)

D	$\frac{Q}{D^{5/2}}$					
	1.4	1.5	1.6	1.7	1.8	1.9
5.0	.00493	.00566	.00644	.00727	.00815	.00908
5.5	.00471	.00541	.00616	.00695	.00779	.00868
6.0	.00452	.00519	.00591	.00667	.00748	.00833
6.5	.00435	.00500	.00569	.00642	.00720	.00802
7.0	.00420	.00483	.00549	.00620	.00695	.00774
7.5	.00407	.00467	.00531	.00600	.00673	.00749
8.0	.00395	.00453	.00515	.00582	.00652	.00727
8.5	.00383	.00440	.00501	.00565	.00634	.00706
9.0	.00373	.00428	.00487	.00550	.00617	.00687
9.5	.00364	.00418	.00475	.00536	.00601	.00670
10.0	.00355	.00408	.00464	.00524	.00587	.00654
10.5	.00347	.00398	.00453	.00512	.00573	.00639
11.0	.00339	.00390	.00443	.00500	.00561	.00625
11.5	.00332	.00381	.00434	.00490	.00549	.00612
12.0	.00326	.00374	.00425	.00480	.00538	.00600
12.5	.00319	.00367	.00417	.00471	.00528	.00588
13.0	.00314	.00360	.00410	.00462	.00518	.00577
13.5	.00308	.00354	.00402	.00454	.00509	.00567
14.0	.00303	.00348	.00395	.00446	.00500	.00558
14.5	.00298	.00342	.00389	.00439	.00492	.00548
15.0	.00293	.00336	.00383	.00432	.00484	.00540
15.5	.00288	.00331	.00377	.00425	.00477	.00531
16.0	.00284	.00326	.00371	.00419	.00470	.00523
16.5	.00280	.00321	.00366	.00413	.00463	.00516
17.0	.00276	.00317	.00361	.00407	.00456	.00509
17.5	.00272	.00313	.00356	.00402	.00450	.00502
18.0	.00269	.00308	.00351	.00396	.00444	.00495
18.5	.00265	.00305	.00346	.00391	.00438	.00489
19.0	.00262	.00301	.00342	.00386	.00433	.00482
19.5	.00259	.00297	.00338	.00381	.00428	.00477
20.0	.00256	.00293	.00334	.00377	.00423	.00471
20.5	.00253	.00290	.00330	.00373	.00418	.00465
21.0	.00250	.00287	.00326	.00368	.00413	.00460

Table 3 (cont'd)

D	$\frac{Q}{D^{5/2}}$					
	2.0	2.1	2.2	2.3	2.4	2.5
5.0	.01006	.01110	.01218	.01331	.01449	.01572
5.5	.00962	.01061	.01164	.01272	.01385	.01503
6.0	.00923	.01018	.01117	.01221	.01329	.01442
6.5	.00889	.00980	.01075	.01175	.01280	.01389
7.0	.00858	.00946	.01038	.01135	.01236	.01341
7.5	.00830	.00916	.01005	.01098	.01196	.01298
8.0	.00805	.00888	.00975	.01065	.01160	.01258
8.5	.00783	.00863	.00947	.01035	.01127	.01223
9.0	.00762	.00840	.00922	.01007	.01097	.01190
9.5	.00742	.00818	.00898	.00982	.01069	.01160
10.0	.00725	.00799	.00877	.00958	.01043	.01132
10.5	.00708	.00781	.00857	.00936	.01020	.01106
11.0	.00693	.00764	.00838	.00916	.00997	.01082
11.5	.00678	.00748	.00821	.00897	.00976	.01060
12.0	.00665	.00733	.00804	.00879	.00957	.01038
12.5	.00652	.00719	.00789	.00862	.00939	.01018
13.0	.00640	.00705	.00774	.00846	.00921	.01000
13.5	.00629	.00693	.00760	.00831	.00905	.00982
14.0	.00618	.00681	.00747	.00817	.00890	.00965
14.5	.00608	.00670	.00735	.00803	.00875	.00949
15.0	.00598	.00659	.00723	.00791	.00861	.00934
15.5	.00589	.00649	.00712	.00778	.00848	.00920
16.0	.00580	.00639	.00702	.00767	.00835	.00906
16.5	.00571	.00630	.00691	.00756	.00823	.00893
17.0	.00563	.00621	.00682	.00745	.00811	.00880
17.5	.00556	.00613	.00672	.00735	.00800	.00868
18.0	.00548	.00605	.00664	.00725	.00790	.00857
18.5	.00541	.00597	.00655	.00716	.00779	.00846
19.0	.00535	.00589	.00647	.00707	.00770	.00835
19.5	.00528	.00582	.00639	.00698	.00760	.00825
20.0	.00522	.00575	.00631	.00690	.00751	.00815
20.5	.00516	.00568	.00624	.00682	.00742	.00806
21.0	.00510	.00562	.00617	.00674	.00734	.00796

Table 3 (cont'd)

D	$\frac{Q}{D^{5/2}}$						
	2.6	2.7	2.8	2.9	3.0	3.1	3.2
5.0	.01701	.01834	.01972	.02116	.02264	.02418	.02576
5.5	.01626	.01753	.01885	.02022	.02164	.02311	.02462
6.0	.01560	.01682	.01809	.01941	.02077	.02218	.02363
6.5	.01502	.01620	.01742	.01868	.02000	.02135	.02275
7.0	.01450	.01564	.01682	.01804	.01930	.02061	.02196
7.5	.01403	.01513	.01628	.01746	.01868	.01995	.02126
8.0	.01361	.01468	.01579	.01693	.01812	.01935	.02062
8.5	.01323	.01426	.01534	.01645	.01761	.01880	.02003
9.0	.01287	.01388	.01493	.01601	.01714	.01830	.01950
9.5	.01255	.01353	.01455	.01563	.01670	.01784	.01900
10.0	.01224	.01320	.01420	.01523	.01630	.01741	.01855
10.5	.01196	.01290	.01388	.01489	.01593	.01701	.01812
11.0	.01170	.01262	.01357	.01456	.01558	.01664	.01773
11.5	.01146	.01236	.01329	.01426	.01526	.01629	.01736
12.0	.01123	.01211	.01303	.01397	.01495	.01597	.01701
12.5	.01102	.01188	.01278	.01370	.01467	.01566	.01669
13.0	.01081	.01166	.01254	.01345	.01440	.01537	.01638
13.5	.01062	.01145	.01232	.01321	.01414	.01510	.01609
14.0	.01044	.01126	.01211	.01299	.01390	.01484	.01581
14.5	.01027	.01107	.01191	.01277	.01367	.01460	.01555
15.0	.01010	.01090	.01172	.01257	.01345	.01436	.01531
15.5	.00995	.01073	.01154	.01238	.01324	.01414	.01507
16.0	.00980	.01057	.01137	.01219	.01305	.01393	.01484
16.5	.00966	.01041	.01120	.01201	.01286	.01373	.01463
17.0	.00952	.01027	.01104	.01185	.01268	.01354	.01442
17.5	.00939	.01013	.01089	.01168	.01250	.01335	.01423
18.0	.00927	.00999	.01075	.01153	.01234	.01317	.01404
18.5	.00915	.00987	.01061	.01138	.01218	.01300	.01386
19.0	.00903	.00974	.01048	.01124	.01203	.01284	.01368
19.5	.00892	.00962	.01035	.01110	.01188	.01268	.01352
20.0	.00882	.00951	.01022	.01097	.01174	.01253	.01335
20.5	.00871	.00940	.01011	.01084	.01160	.01239	.01320
21.0	.00861	.00929	.00999	.01072	.01147	.01225	.01305

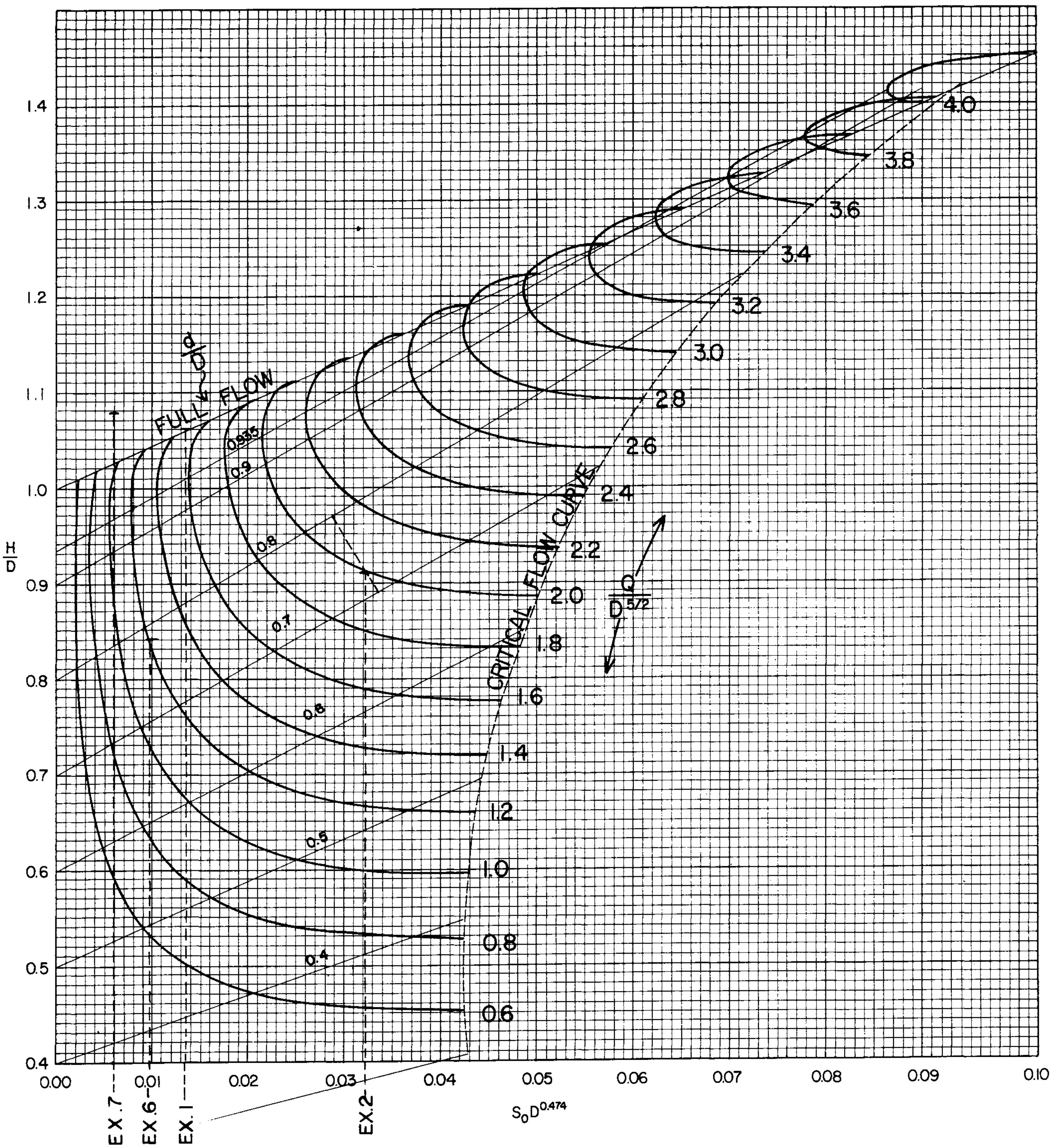


Figure 1 BACKWATER FLOW IN PIPE

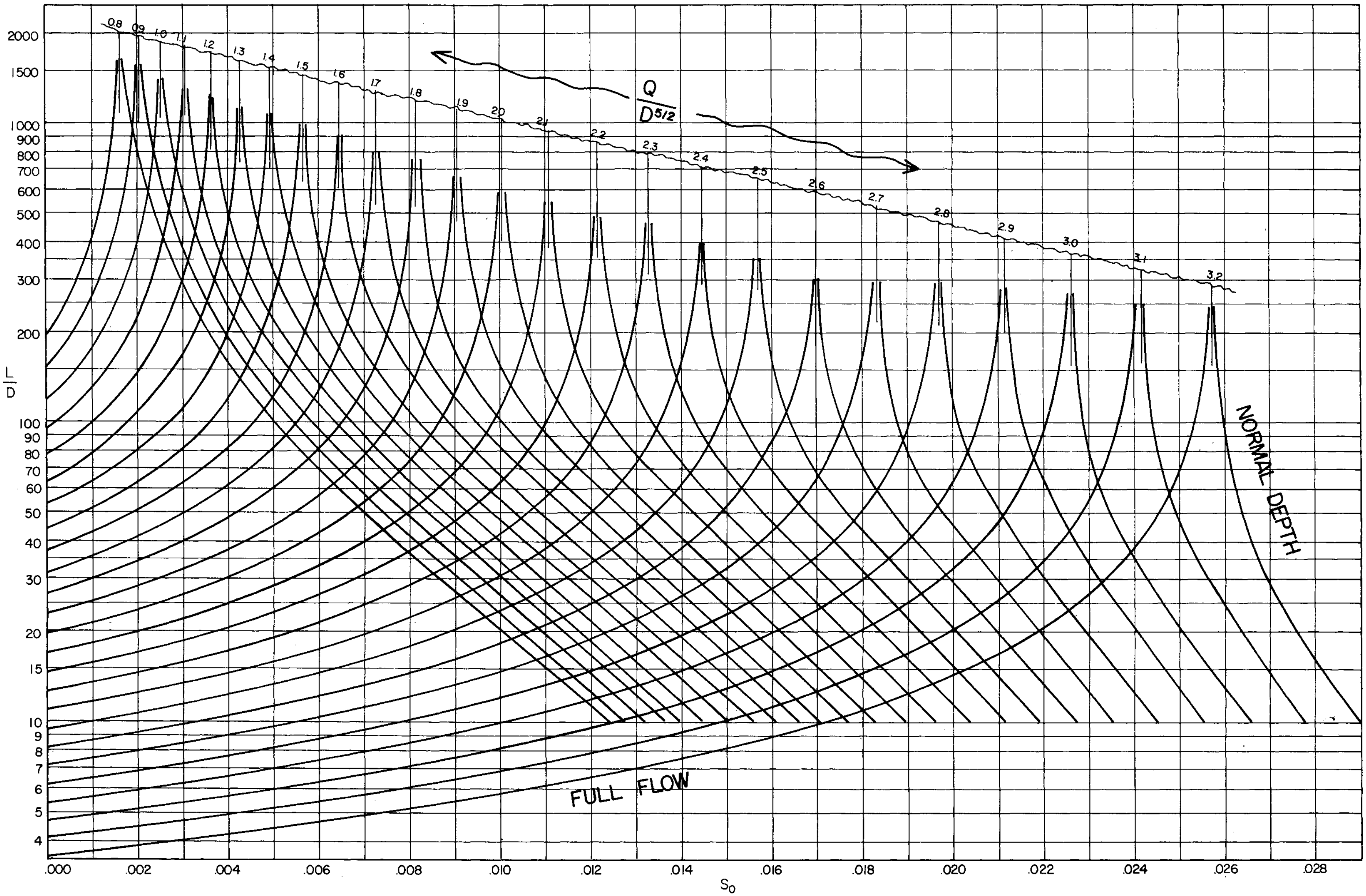


Figure 2 BACKWATER CURVE LENGTH D=5Ft.

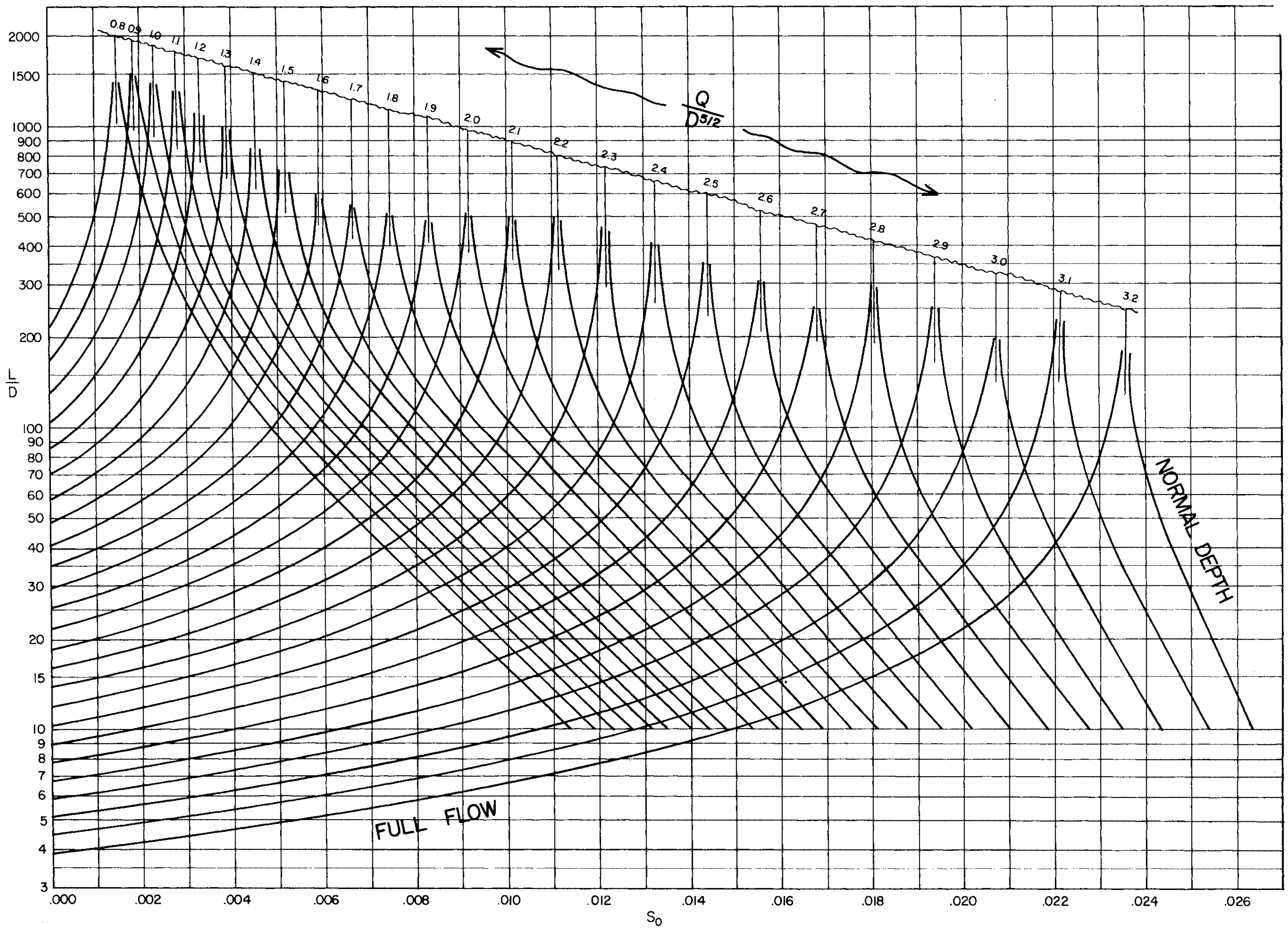


Figure 3 BACKWATER CURVE LENGTH D = 6 Ft.

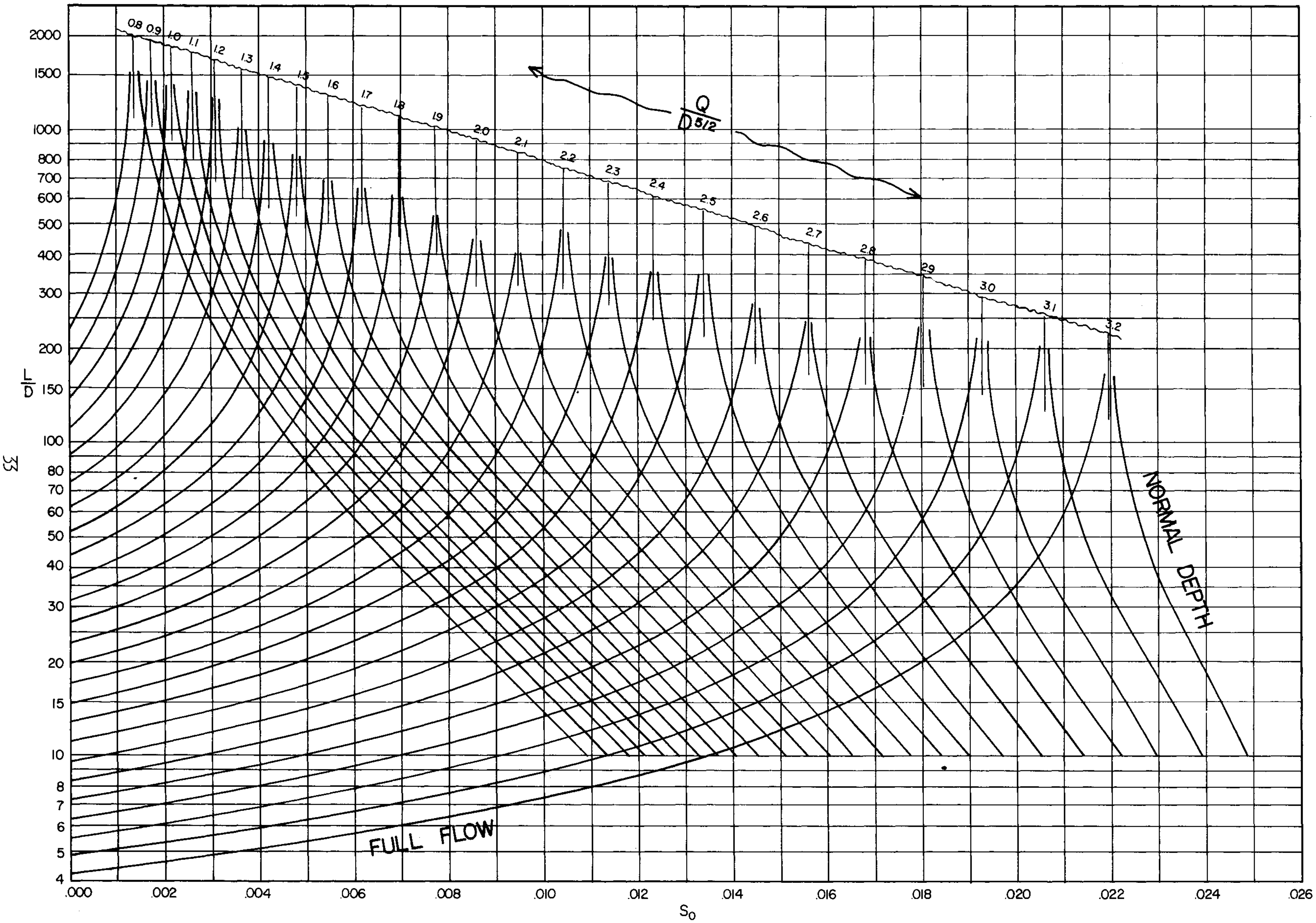


Figure 4 BACKWATER CURVE LENGTH D = 7 Ft.

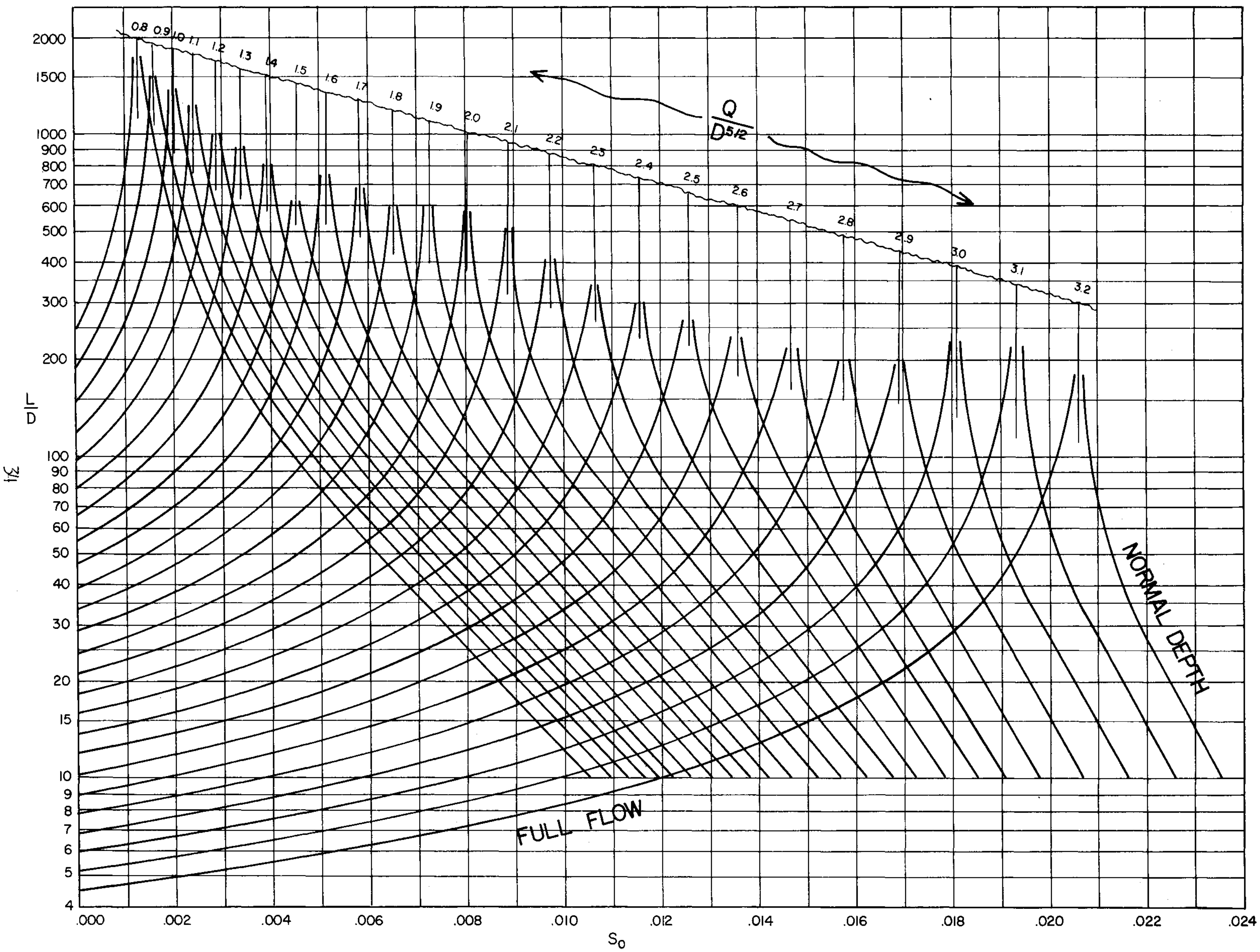


Figure 5 BACKWATER CURVE LENGTH D = 8 Ft.

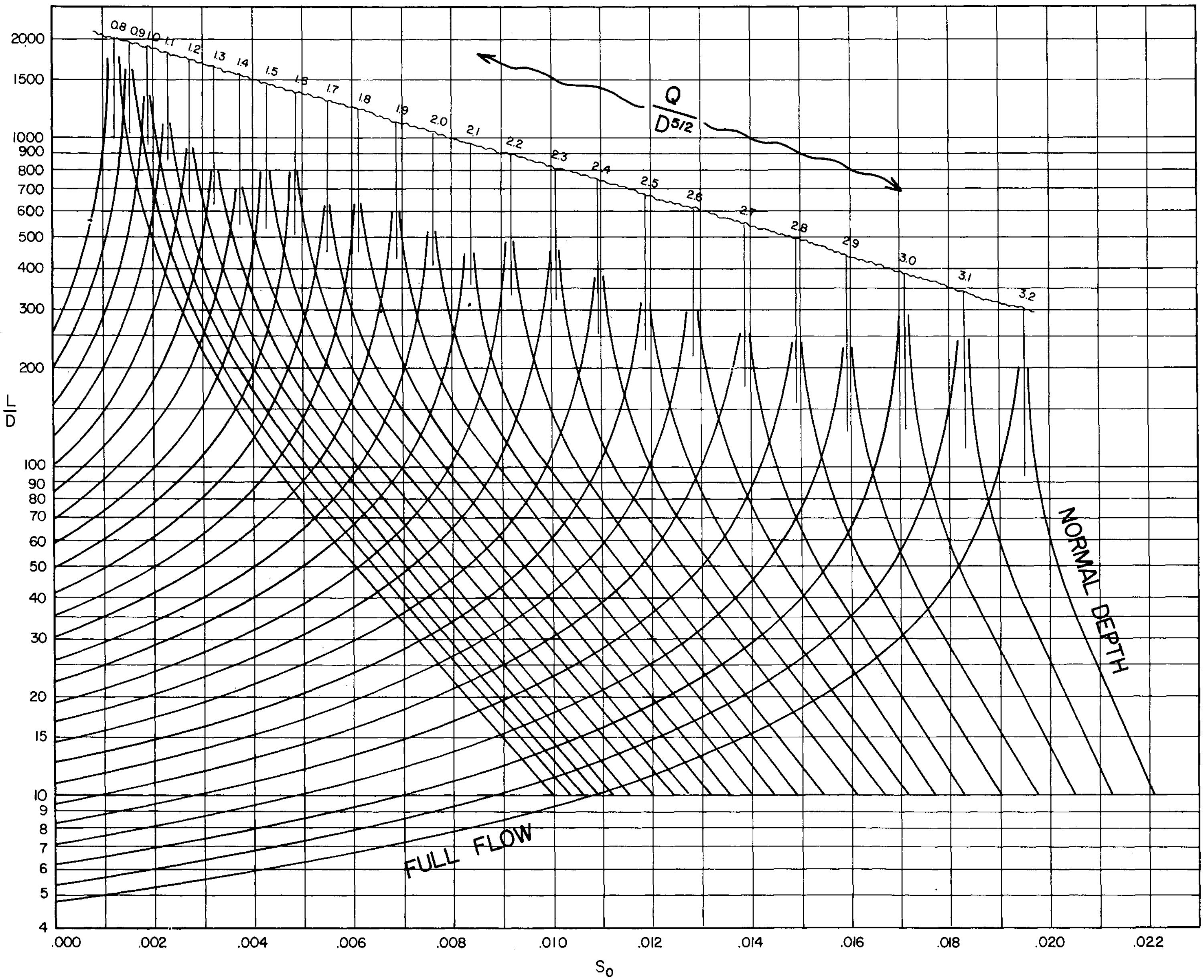


Figure 6 BACKWATER CURVE LENGTH D= 9 Ft.

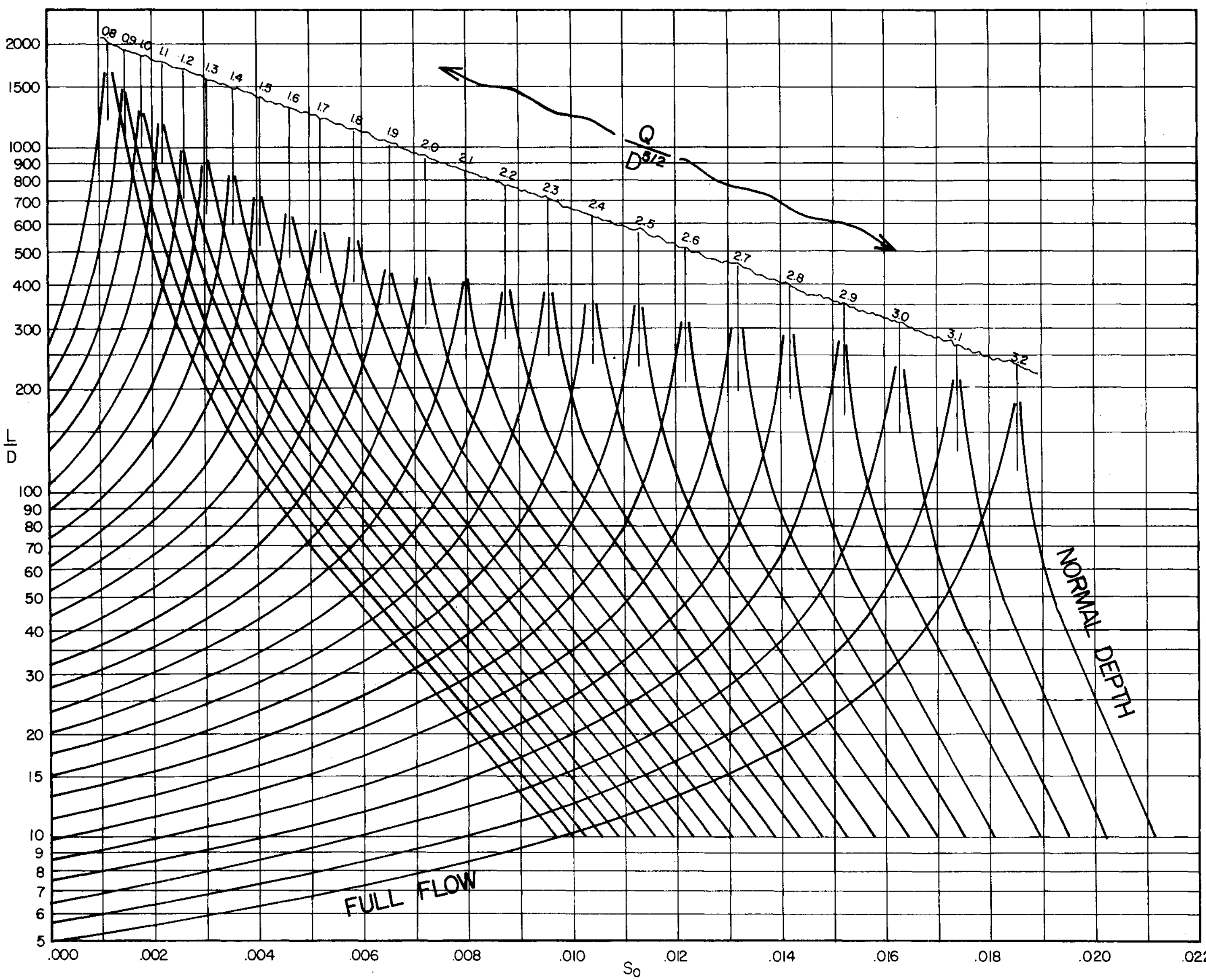


Figure 7 BACKWATER CURVE LENGTH D= 10 Ft.

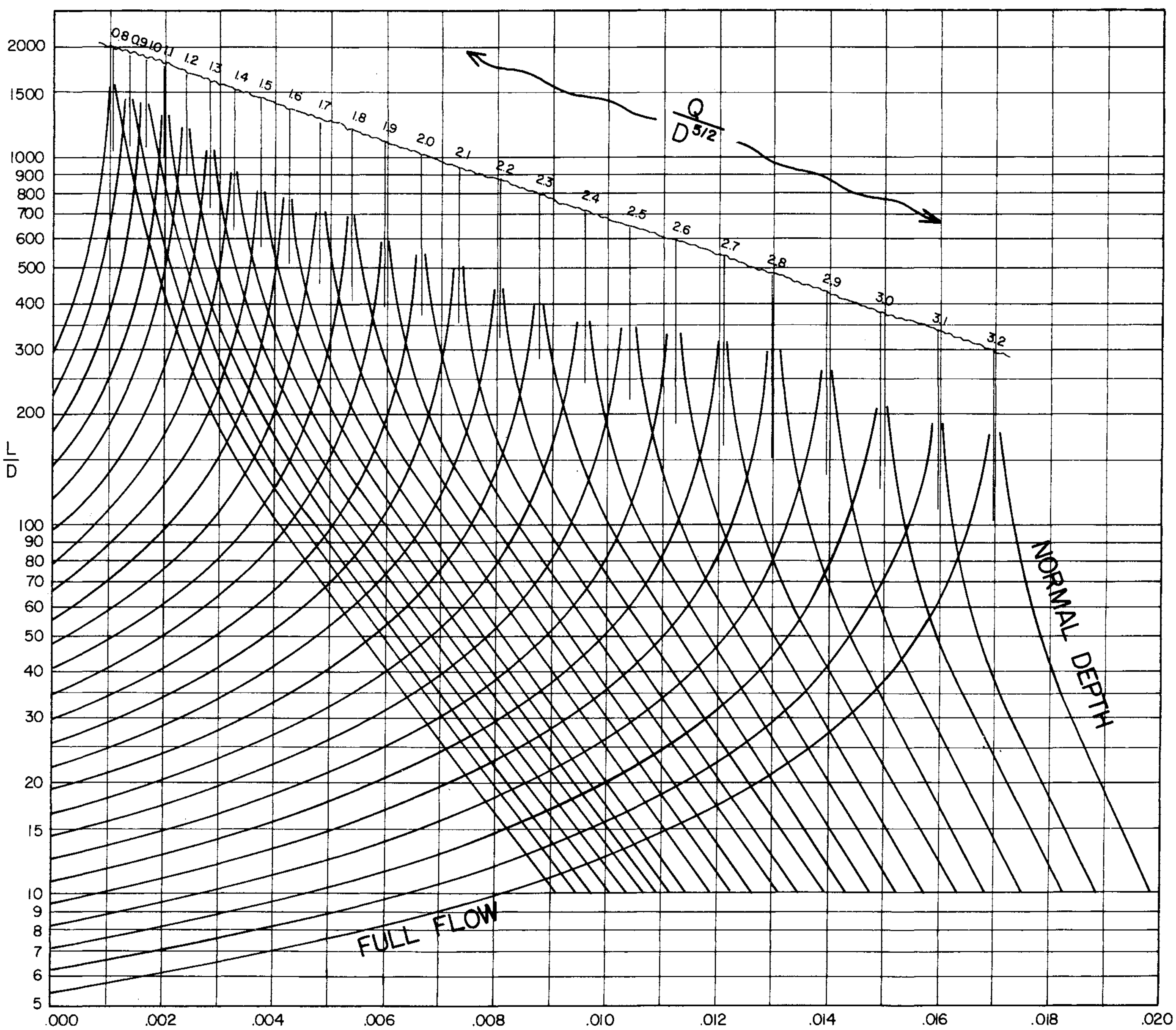


Figure 8 BACKWATER CURVE LENGTH D= 12 Ft.

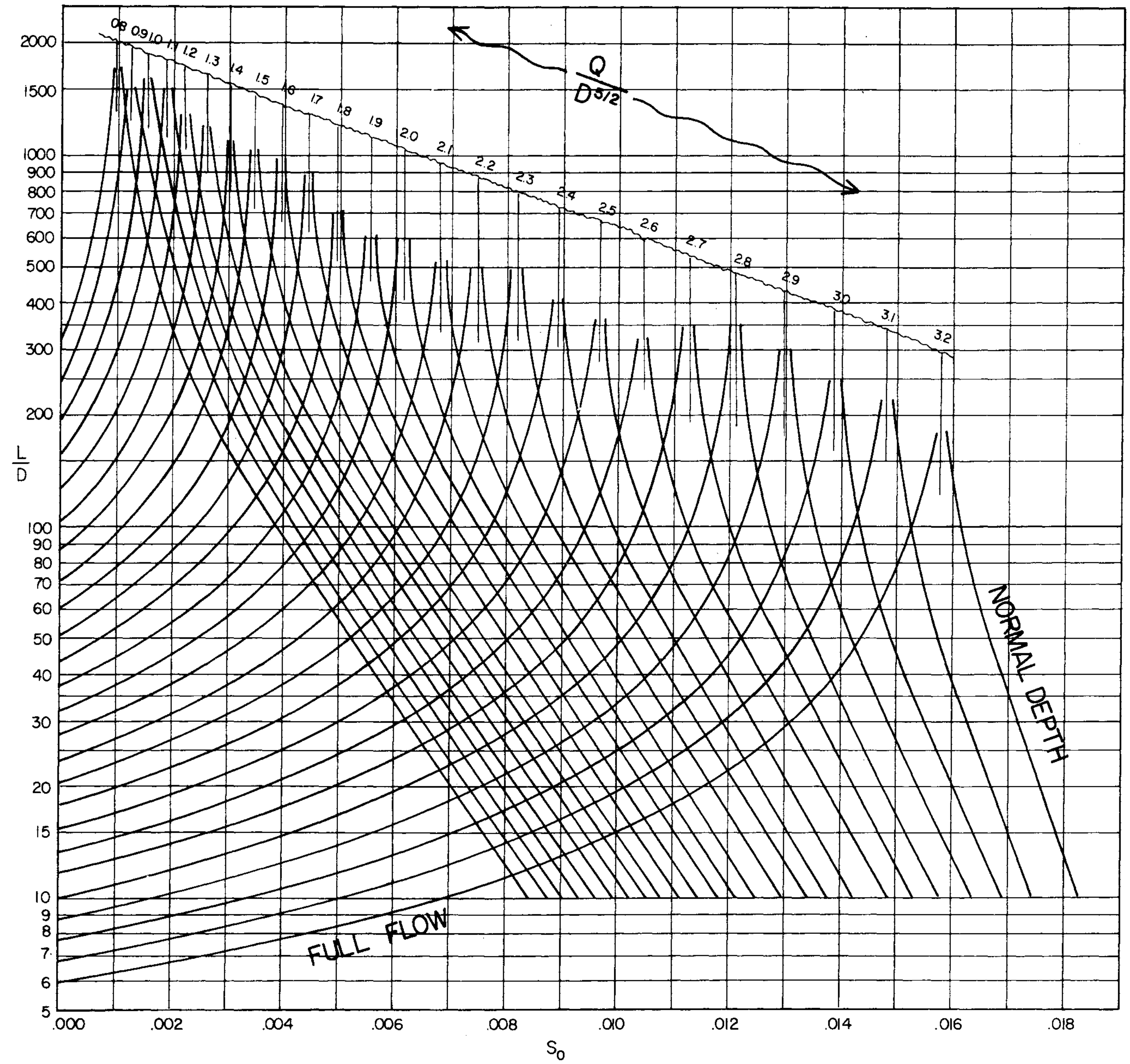


Figure 9 BACKWATER CURVE LENGTH D=14 Ft.

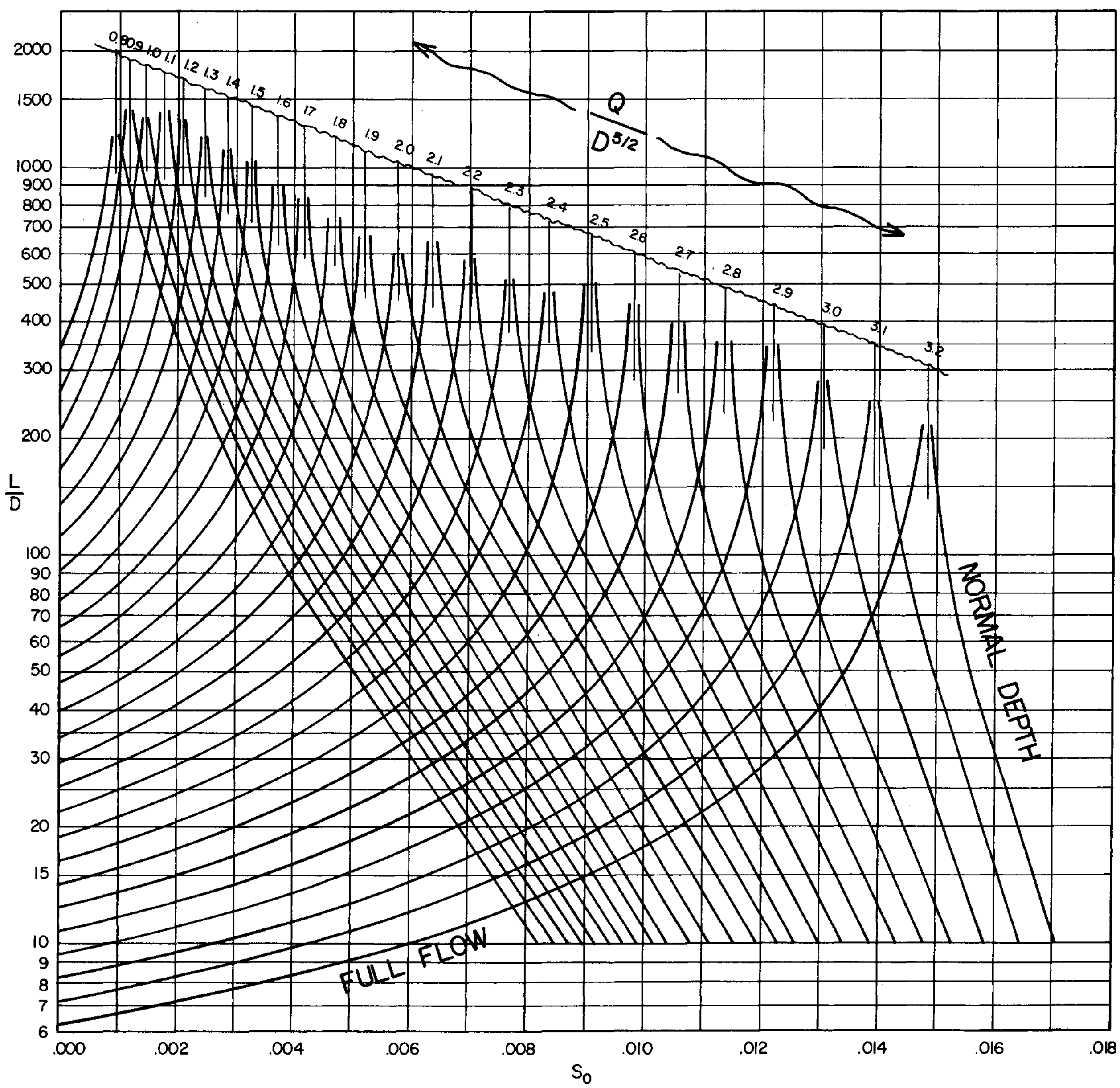


Figure 10 BACKWATER CURVE LENGTH D = 16 Ft.

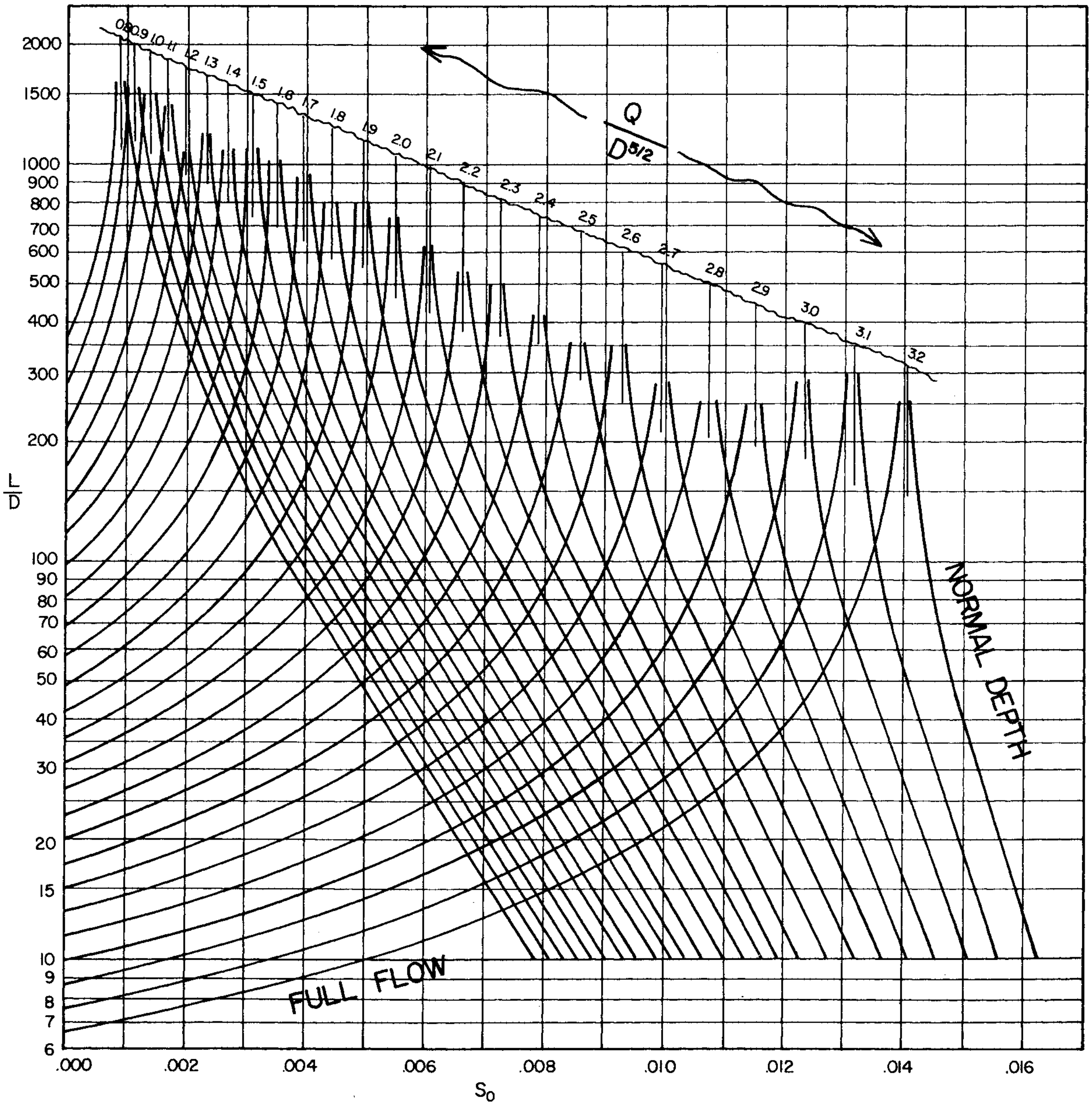


Figure 11 BACKWATER CURVE LENGTH D= 18 Ft.

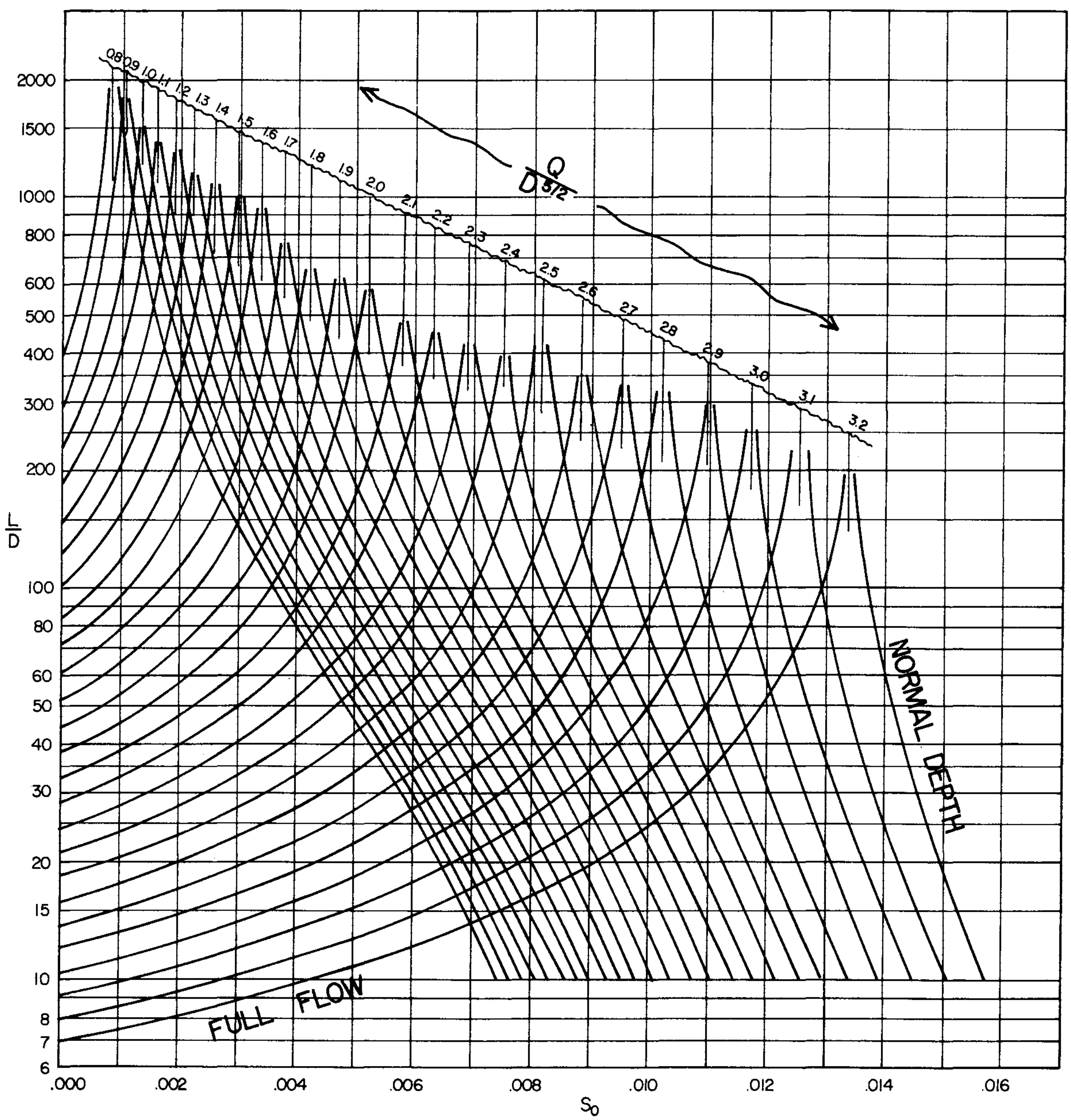


Figure 12 BACKWATER CURVE LENGTH D = 20 Ft.

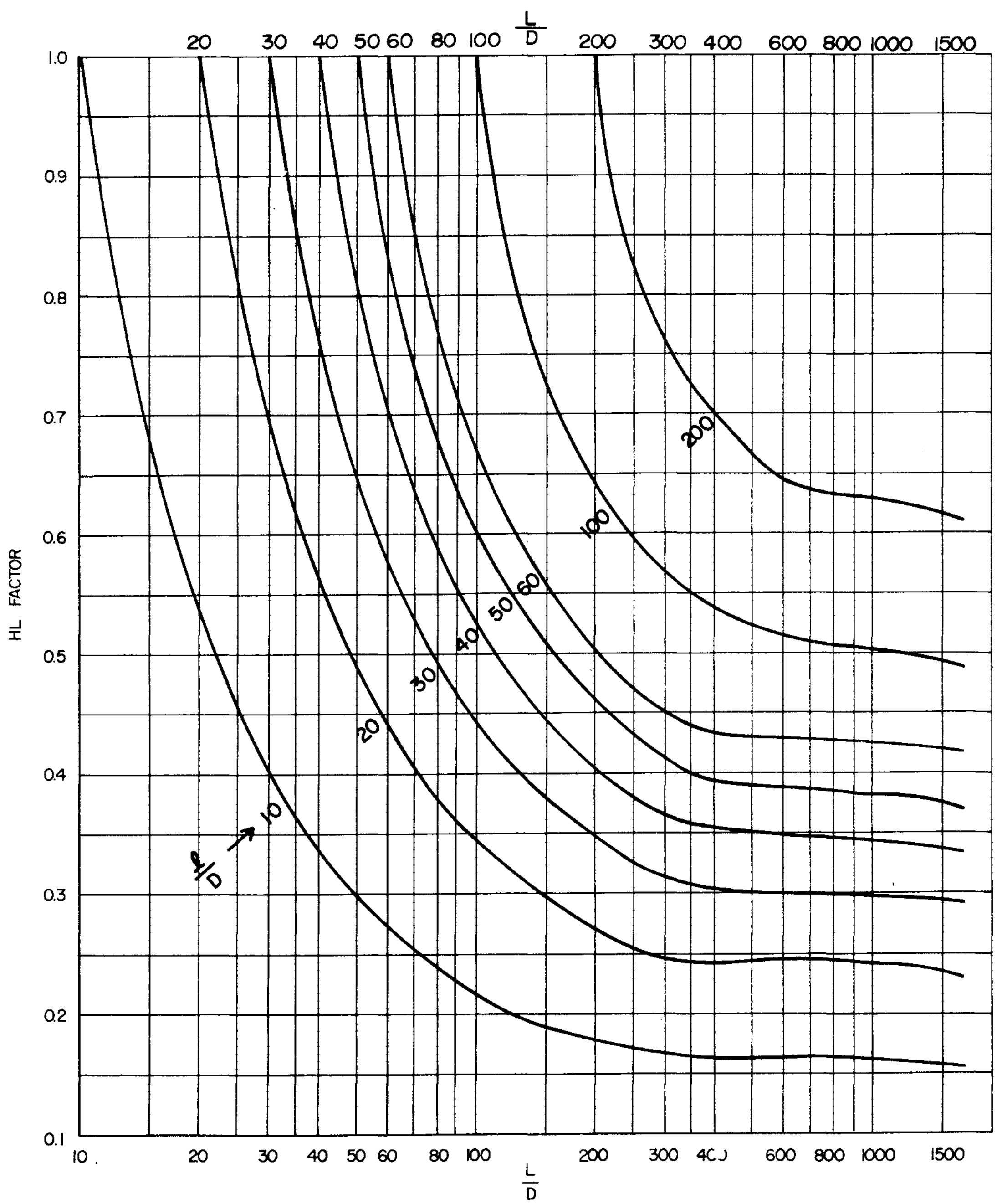


Figure 13 HL FACTORS FULL FLOW BACKWATER CURVES

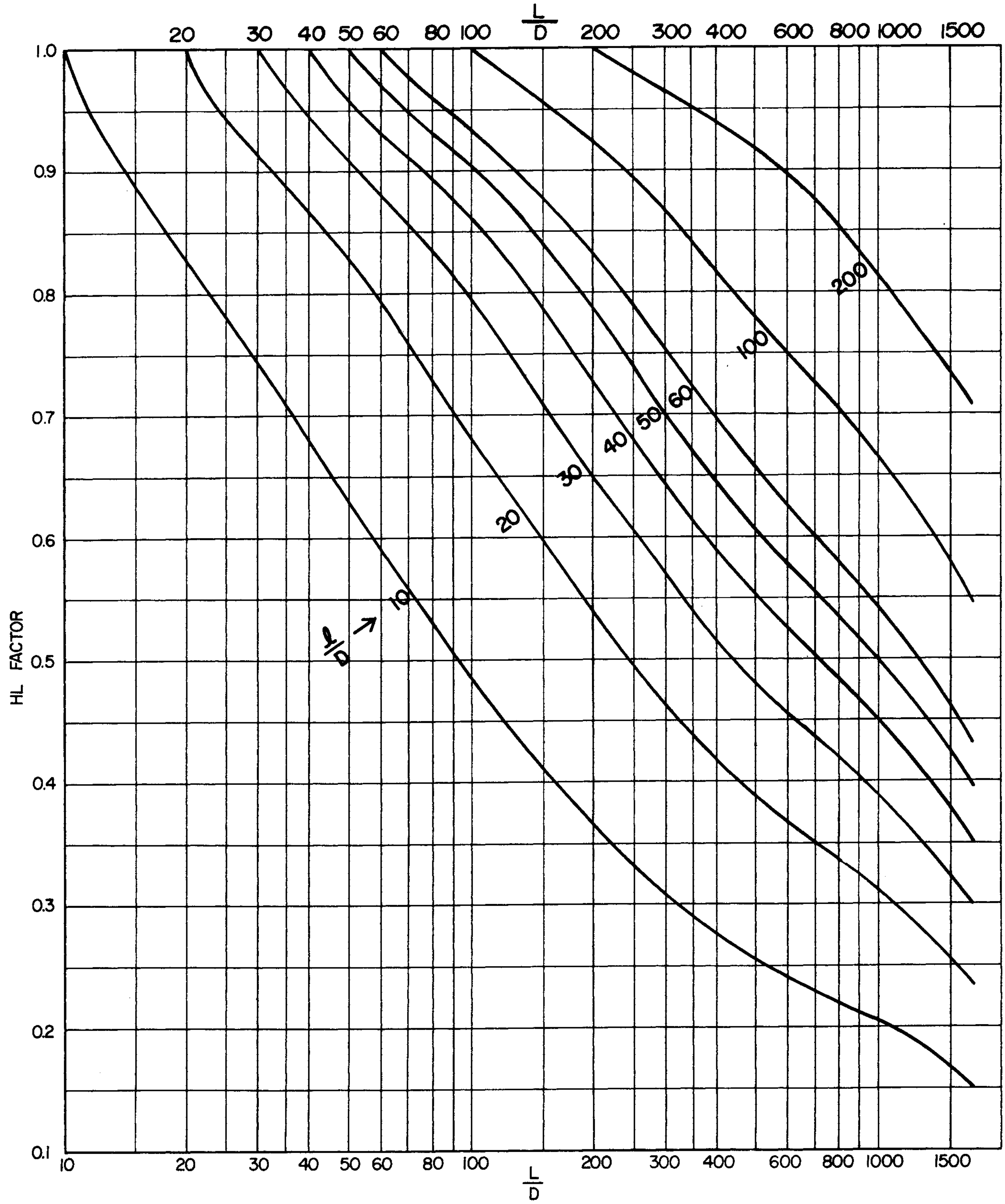


Figure 14 HL FACTORS NORMAL DEPTH BACKWATER CURVES

APPENDIX B: REFERENCES

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