HYDRAULIC DESIGN SERIES NO. 3

DESIGN CHARTS FOR OPEN-CHANNEL FLOW

U.S. Department
of Transportation
Federal Highway
Administration

Other Publications of the Hydraulic Design Series

Hydraulics of Bridge Waterways

Hydraulics of Bridge Waterways, Hydraulic Design Series No. 1, Second Edition, presents simplified methods for computing backwater caused by bridges. These methods were developed from extensive model tests and actual measurements of flow on streams with wide flood plains. The empirical curves and methods of calculation contained in the new publication have a much wider range of application than those of the first edition, published in 1960, which were based principally on hydraulic model studies. Additional field data collected during floods were available for the second edition. A considerable amount of new material has been added including chapters on partially inundated superstructures, the proportioning of spur dikes at bridge abutments, and supercritical flow under a bridge together with examples.

The nature of this publication is indicated by the chapter titles: computation of backwater; difference in water level across approach embankments; configuration of backwater; dual bridges; abnormal stage-discharge conditions; effects of scour on backwater; superstructures partially inundated; spur dikes; flow passes through critical depth; preliminary field and design procedures; illustrative examples; and discussion of procedures and limitations of method.

Hydraulics of Bridge Waterways is available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402. Stock No. 050–001–0064–4.

Peak Rates of Runoff from Small Watersheds

Peak Rates of Runoff from Small Watersheds, Hydraulic Design Series, has been discontinued.

Design of Roadside Drainage Channels

Design of Roadside Drainage Channels, the fourth in a series on the hydraulic design of highway drainage structures by the Federal Highway Administration, discusses methods of open-channel design including determining size of channel and protection required to prevent erosion. Principles and procedures are explained, but no set of rules can be furnished that will apply to all of the many diverse combinations of topography, soil and climate that exist where highways are built. Design of roadside drainage channels will continue to require an engineer well versed in hydraulic theory and in highway drainage practice.

Design of Roadside Drainage Channels is available from the Federal Highway Administration, Hydraulics Branch, HNG–31, Washington, D.C. 20590.

CONTENTS

FIGURES AND CHARTS

Figures

Charts

(A quick index of the charts, grouped by purpose of use, appears on the outside back cover.)

Chapter 1.—INTRODUCTION

1.1 Content of publication. This publication contains charts which provide direct solution of the Manning equation for uniform flow in open prismatic channels of various cross sections; instructions for using the charts; a table of recommended values of n in the Manning equation, and tables of permissible velocities in earth and vegetated channels; instructions for constructing charts similar to those presented; and a nomograph for use in the solution of the Manning equation. A quick index to the chart numbers is given on the outside back cover.

The publication is not intended to be a textbook, and it is assumed that users will be familiar with hydraulic theory and design. However, a brief discussion of the principles of open-channel flow is presented in chapter 2. No attempt has been made to cover the subject of flow in natural channels except as these may approximate the uniform prismatic channels covered in the charts.

The charts fall into two major groups: The first group, Nos. 1–51, consists of separate charts for various size channels of a given shape, with all functions on each chart; the second group, Nos. 52–82, has charts covering a wide range of sizes but with only one or two functions on each chart.

The open-channel flow charts in the first group give a direct and rapid determination of normal depth and normal velocity of flow in a channel of given cross section, roughness, and slope, carrying a known discharge. Values can be read to two significant figures, which is sufficiently accurate for ordinary design purposes. While the open-channel flow charts were drawn for a specific value of n, they can also be used for any other value of n by following the instructions given. For circular sections, two other n values are provided by additional scales.

The second group of charts, Nos. 52–82, requires only five charts to cover the hydraulic functions of a wide range of sizes of channels of a given shape and roughness. They have some small disadvantage in that normal depth must be determined by three steps, involving two charts and a simple calculation. Determination of friction slope in part-full flow also requires three similar steps. On the other hand, critical depth, critical slope, and specific head at critical depth may be read directly from these charts, and probably more accurately, than from the open-channel flow charts. The latter actually give only critical depth, critical slope, and critical velocity but require computation of velocity head to obtain specific head at critical depth.

The designer is cautioned not to use the open-channe flow charts presented in this publication as a means of es timating the size of culvert required for a given discharge because the hydraulics of culverts is not simply uniform flow at normal depth. The head required to get flow into a culvert may be several times the head required to maintain uniform flow. Other publications proposed for the Bureau of Public Roads hydraulic design series will deal with the hydraulic design of culverts.

1.2 Arrangement of publication. A list of symbols, with their definitions, as used in this publication, follows this section. As already mentioned, a brief discussion of the basic principles of flow in open channels is presented in chapter 2.

Chapter 3 contains charts 1–29, and instructions for their use, covering rectangular, trapezoidal, and triangular cross-section channels.

Chapter 4 includes charts 30–34, for flow in grass-lined channels where channel resistance (called retardance) varies as the product of the velocity and the hydraulic radius.

Chapter 5 contains charts 35–60, for circular pipe channels; chapter 6 contains charts 61–73, for pipe-arch channels; and chapter 7 contains charts 74–82, for oval concrete pipe channels.

For convenience of the designer who may have frequent recourse to this publication in his work, all of the tables are grouped together in Appendix A. These include table 1, recommended values of n in the Manning equation; tables 2 and 3, permissible velocities in earth and vegetated channels; table 4, factors for adjustment of Q for increased resistance caused by friction against the top of a closed rectangular conduit; and table 5, a guide to the selection of retardance curves for use in connection with grassed channels.

Designers may wish to prepare open-channel flow charts for cross sections other than those represented on the charts contained in this publication. This may well be worthwhile for sections used sufficiently to justify the effort. The computation and construction of the charts is relatively simple and reasonably rapid. Instructions for preparing open-channel flow charts, including those for grass-lined channels, will be found in appendix B.

Chart 83, in appendix C, provides a ready means for the graphic solution of the Manning equation.

1.3 Definition of symbols. The symbols used in the ensuing text, figures, and charts are defined below. Units of measurement used with the symbols are given in parentheses following the definition.

A = Area of cross section of flow (sq. ft.).

α = Kinetic energy (velocity head) coefficient; assumed as 1.0 on the charts.

B = Width of rectangular channel or conduit (ft.).

b = Bottom width of trapezoidal channel (ft.).

C.M. = Abbreviation for corrugated metal.

D = Height of a conduit (ft.).

d = Depth of flow at any section (ft.).

d_c = Critical depth of flow in a channel (ft.).

d_m = Mean depth $= A/T$ (ft.).

d_n = Normal depth of flow in a uniform channel for steady flow (ft.).

g = Acceleration of gravity $= 32.2$ (ft./sec.^{2}).

H_c = Specific head at minimum energy $= d_c + V_c^2/2g$ (ft.).

n = Manning's roughness coefficient.

Q = Rate of discharge (c.f.s.).

R = Hydraulic radius $= A/WP$ (ft.).

S = Slope of total head line (energy gradient) (ft./ft.).

S_c = That particular slope of a given uniform conduit operating as an open channel at which normal depth equals critical depth for a given Q (ft./ft.).

S_f = Friction slope in a conduit. This represents the rate of loss of head in a conduit due to friction. In a uniform channel with steady flow, it is equal to the slope of the total head line (ft./ft.).

S_0 = Slope of the flow line of a conduit (bed slope). With a steady uniform flow, the water surface, the total head line, and the flow line are all parallel and $S_0 = S_f$ (ft./ft.).

T = Top width of the water surface in a channel (ft.).

V = Mean velocity of flow (f.p.s.).

V_c = Mean velocity of flow in a channel when flow is at critical depth (f.p.s.).

V_n = Mean velocity of flow in a channel when flow is at normal depth. Normal depth and normal velocity apply only to uniform flow with a free water surface. These conditions will be approached with a steady discharge in a uniform channel of length sufficient to establish uniform flow (f.p.s.).

WP = Wetted perimeter; the length of line of contact between the flowing water and the conduit, measured on a cross section (ft.).

Z = Elevation of bed of channel above an arbitrary datum; also, the reciprocal of cross slope of a shallow triangular channel (ft.).

Chapter 2.—PRINCIPLES OF FLOW IN OPEN CHANNELS

2.1 Design of highway drainage channels. The design of a highway drainage channel to carry a given discharge is accomplished in two parts. The first part of the design involves the computation of a channel section which will carry the design discharge on the available slope. This chapter briefly discusses the principles of flow in open channels and the use of the Manning equation for computing the channel capacity.

The second part of the design is the determination of the degree of protection required to prevent erosion in the drainage channel. This can be done by computing the velocity in the channel at the design discharge, using the Manning equation, and comparing the calculated velocity with that permissible for the type of channel lining used. (Permissible velocities are shown in tables 2 and 3, on page 101.) A change in the type of channel lining will require a change in channel size unless both linings have the same roughness coefficient.

2.2 Types of flow. Flow in open channels is classified as steady or unsteady. The flow is said to be steady when the rate of discharge is not varying with time. In this chapter, the flow will be assumed to be steady at the discharge rate for which the channel is to be designed. Steady flow is further classified as uniform when the channel cross section, roughness, and slope are constant; and as nonuniform or varied when the channel properties vary from section to section.

Depth of flow and the mean velocity will be constant for steady flow in a uniform channel.

2.3 Uniform flow. With a given depth of flow d in a uniform channel, the mean velocity V may be computed by the Manning equation:

$$V=\frac{1.49}{n}R^{2/3}S^{1/2} \qquad (1)$$

in which:

R = Hydraulic radius = A/WP = area of cross section of flow divided by wetted perimeter.

S = Slope of total head line.

n = Manning roughness coefficient.

The discharge Q is then:

$$Q=AV \qquad (2)$$

The Manning equation will give a reliable estimate of velocity only if the discharge, channel cross section, roughness, and slope are constant over a sufficient distance to establish uniform flow conditions. Strictly speaking, uniform flow conditions seldom, if ever, occur in nature because channel sections change from point to point. For practical purposes in highway engineering, however, the Manning equation can be applied to most streamflow problems by making judicious assumptions.

When the requirements for uniform flow are met, the depth d and the velocity V_n are said to be normal and the slopes of the water surface and the channel are parallel. For practical purposes, in highway drainage design, minor undulations in streambed or minor deviations from the mean (average) cross section can be ignored as long as the mean (average) slope of the channel can be represented as a straight line.

The Manning equation can readily be solved either graphically (using chart 83, appendix C) or mathematically for the average velocity V in a given channel if the normal depth d_n is known, because the various factors in the equation are known or can be determined (the hydraulic radius can be computed from the normal depth in the given channel). Discharge Q is then the product of the velocity V and the area of flow A. More commonly, however, the depth is the unknown quantity, and without channel charts the solution requires repeated trials, using special tables such as those in the Corps of Engineers *Hydraulic Tables* and the Bureau of Reclamation *Hydraulic and Excavation Tables*.[1]

The charts in this bulletin provide a direct solution of the Manning equation for many channels of rectangular, trapezoidal, and circular (pipe) cross section. A pipe flowing less than full operates as an open channel.

2.4 Energy of flow. Flowing water contains energy in two forms, potential and kinetic. The potential energy at a particular point is represented by the depth of the water plus the elevation of the channel bottom above a convenient datum plane. The kinetic energy, in feet, is represented by the velocity head, $V^2/2g$. In channel-flow problems it is often desirable to consider the energy content with respect to the channel bottom. This is called the specific energy or specific head and is equal to the depth of water plus the velocity head, $d+V^2/2g$. At other times it is desirable to use the total energy content (total head), which is the specific head plus the elevation of the channel

[1] *Hydraulic Tables*, prepared under the direction of the Corps of Engineers, War Department, by the Mathematical Tables Project, Federal Works Agency, Work Projects Administration for the City of New York, 1944. Published by the U.S. Government Printing Office.

Hydraulic and Excavation Tables, Bureau of Reclamation, Department of the Interior, 11th edition, 1957. Published by the U.S. Government Printing Office.

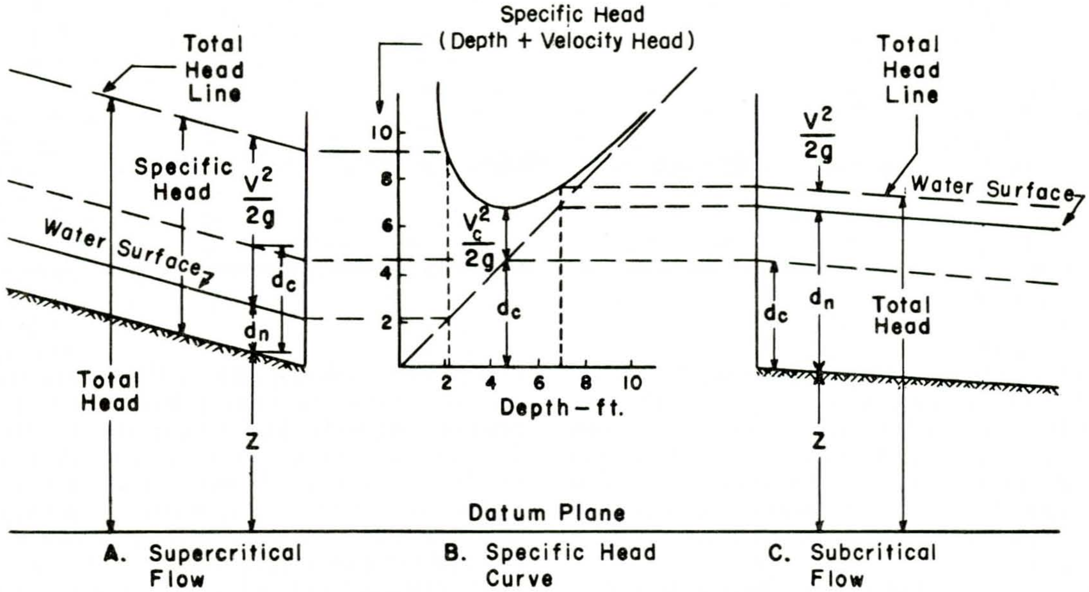


Figure 1.—Definition sketch of specific head.

bottom above a selected datum. For example, total head may be used in applying the energy equation, which states that the total head (energy) at one point in a channel carrying a flow of water is equal to the total head (energy) at any point downstream plus the energy (head) losses occurring between the two points. The energy (Bernoulli) equation is usually written:

$$d_1+\frac{V_1^2}{2g}+Z_1=d_2+\frac{V_2^2}{2g}+Z_2+h_{loss} \qquad (3)$$

In the equation, cross section 2 (subscript 2) is downstream from cross section 1 (subscript 1), Z is the elevation of channel bottom, and h_{loss} represents loss of head between cross sections 1 and 2. A convenient way of showing specific head is to plot the water surface and the specific head lines above a profile of the channel bottom (see fig. 1, sketches A and C).

Note in figure 1 that the line obtained by plotting velocity head above the water surface is the same line as that obtained by plotting specific head above the channel bottom. This line represents the total energy, potential and kinetic, of the flow in the channel and is called the "total head line" or "total energy line".

The slope (gradient) of the energy line is a measure of the friction slope or rate of energy head loss due to friction. The total head loss in length L is equal to $S \times L$. Under uniform flow, the energy line is parallel to the water surface and to the streambed. For flow to occur in a channel, the the total head or energy line must slope negatively (downward) in the direction of flow.

2.5 Critical flow. The relative values of the potential energy (depth) and kinetic energy (velocity head) are important in the analysis of open-channel flow. Consider, for example, the relation of the specific head, $d+V^2/2g$, and the depth d of a given discharge in a given channel that can be placed on various slopes. Plotting values of specific head as ordinates and of the corresponding depth as abscissa, will result in a specific-head curve such as tha shown in figure 1B. The straight, diagonal line is drawn through points where depth and specific head are equal. The line thus represents the potential energy, and the ordinate interval between this line and the specific head curve is the velocity head for the particular depth. A change in the discharge Q or in the channel size or shape will change the position of the curve, but its general shape and location above and to the left of the diagonal line will remain the same. Note that the ordinate at any point on the specific head curve represents the total specific energy, $d+V^2/2g$, at that point. The lowest point on the curve represents flow with the minimum energy content. The depth at this point is known as critical depth d_c, and the corresponding velocity is the critical velocity V_c. With uniform flow, the channel slope at which critical depth occurs is known as the critical slope S_c.

Points on the left of the low point of the specific head curve (fig. 1B) are for channel slopes steeper than critical (supercritical or steep slopes), and indicate relatively shallow depths and high velocities (fig. 1A). Such flow is called supercritical flow. It is difficult to handle because violent wave action occurs when either the direction of flow or the cross section is changed. Flow of this type is common in steep flumes and mountain streams. In supercritical flow, the depth of flow at any point is influenced by a control upstream, usually critical depth.

Points on the right of the low point of the specific head curve (fig. 1B) are for slopes flatter than critical (subcritical or mild slopes) and indicate relatively large depths with low velocities (fig. 1C). Such flow is called subcritical flow. It is relatively easy to handle through transitions because the wave actions are tranquil. Flow of this type is most common in streams in the plains and broad valley regions. In subcritical flow, the depth at any point is influenced by a downstream control, which may be either critical depth or the water surface elevation in a pond or larger downstream channel. Figures 1A and 1C indicate the relationship of supercritical and subcritical flows, respectively, to the specific head curve.

Critical depth d_c is the depth of flow at minimum specific energy content (fig. 1B), and it can readily be determined for the commonly used channel sections. The magnitude of critical depth depends only on the discharge and the shape of the channel, and is independent of the slope or channel roughness. Thus, in any given size and shape of channel, there is only one critical depth for a particular discharge. Critical depth is an important value in hydraulic analyses because it is a control in reaches of nonuniform flow whenever the flow changes from subcritical to supercritical. Typical occurrences of critical depth are: (1) Entrance to a restrictive channel, such as a culvert or flume, on a steep slope; (2) at the crest of an overflow dam or weir; and (3) at the outlet of a culvert or flume discharging with a free fall or into a relatively wide channel or a pond in which the depth is not enough to submerge critical depth in the culvert or flume.

Critical slope is that channel slope, for a particular channel and discharge, at which the normal depth for uniform flow will be the same as the critical depth. Critical slope varies with both the roughness and geometric shape of the channel and with the discharge.

The open-channel flow charts for rectangular, trapezoidal, and circular channels presented in this bulletin have a heavy broken line from which critical depth and critical velocity may be read directly for different values of Q, regardless of channel roughness. Critical slope, however, varies with roughness and must be determined as provided in the instructions.

For large circular cross-section pipes, and for pipe-arch and oval pipe sections, a direct reading can be made on the part-full flow charts for critical depth, specific head, and critical slope (for certain values of n). Determination of critical velocity, however, requires the more involved procedure described in the instructions for the part-full flow charts.

2.6 Nonuniform flow. Truly uniform flow rarely exists in either natural or man-made channels, because changes in channel section, slope, or roughness cause the depths and average velocities of flow to vary from point to point along the channel, and the water surface will not be parallel to the streambed. Flow that varies in depth and velocity along the channel is called nonuniform. Although moderate nonuniform flow actually exists in a generally uniform channel, it is usually treated as uniform flow in such cases. Uniform flow characteristics can readily be computed and the computed values are usually close enough to the actual for all practical purposes. The types of nonuniform flow are innumerable, but certain characteristic types are described in the following paragraphs. Briefly discussed are the characteristics of nonuniform flow, both subcritical and supercritical, together with common types of nonuniform flow encountered in highway drainage design.

With subcritical flow, a change in channel shape, slope, or roughness affects the flow for a considerable distance upstream, and thus the flow is said to be under downstream control. If an obstruction, such as a culvert, causes ponding, the water surface above the obstruction will be a smooth curve asymptotic to the normal water surface upstream and to the pool level downstream (see fig. 2). Another example of downstream control occurs where an abrupt channel enlargement, as at the end of a culvert not flowing full, or a break in grade from a mild to a steep slope, causes a drawdown in the flow profile to critical depth. The water surface profile upstream from a change in section or a break in channel slope will be asymptotic to the normal water surface upstream, but will drop away from the normal water surface on approaching the channel change or break in slope. In these two examples, the flow is nonuniform because of the changing water depth caused by changes in the channel slope or channel section. Direct solution of open-channel flow by the Manning equation or by the charts in this bulletin is not possible in the vicinity of the changes in the channel section or channel slope.

With supercritical flow, a change in channel shape, slope, or roughness cannot be reflected upstream except for very short distances. However, the change may affect the depth of flow at downstream points; thus, the flow is said to be under upstream control. An example is the flow in a steep chute where the water surface profile draws down from critical depth at the chute entrance and approaches the lesser normal depth in the chute (see fig. 3).

Most problems in highway drainage do not require the accurate computation of water surface profiles; however, the designer should know that the depth in a given channel may be influenced by conditions either upstream or downstream, depending on whether the slope is steep (supercritical) or mild (subcritical). Three typical examples of nonuniform flow are shown in figures 2–4 and are discussed in the following paragraphs. The discussion also explains the use of the total head line in analyzing nonuniform flow.

Figure 2 shows a channel on a mild slope, discharging into a pool. The vertical scale is exaggerated to illustrate the case more clearly. Cross section 1 is located at the end of uniform channel flow in the channel and cross section 2 is located at the beginning of the pool. The depth of flow d between sections 1 and 2 is changing and the flow is nonuniform. The water surface profile between the sections is known as a backwater curve and is characteristically very long. The computation of backwater curves is explained in textbooks and handbooks on hydraulics.

Figure 3 shows a channel in which the slope changes from subcritical to supercritical. The flow profile passes through critical depth near the break in slope (section 1). This is true whether the upstream slope is mild, as in the sketch, or whether the water above section 1 is ponded, as would be the case if section 1 were the crest of a spillway of a dam. If, at section 2, the total head were computed, assuming normal depth on the steep slope, it would plot (point a on sketch) above the elevation of total head at

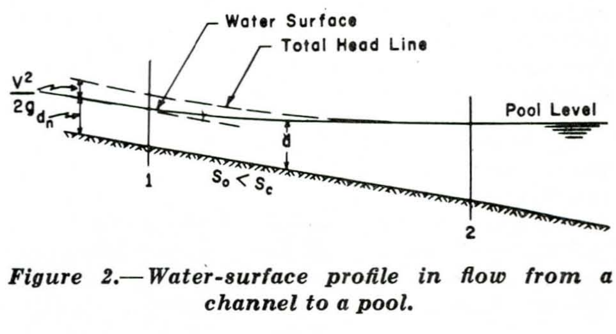


Figure 2.—Water-surface profile in flow from a channel to a pool.

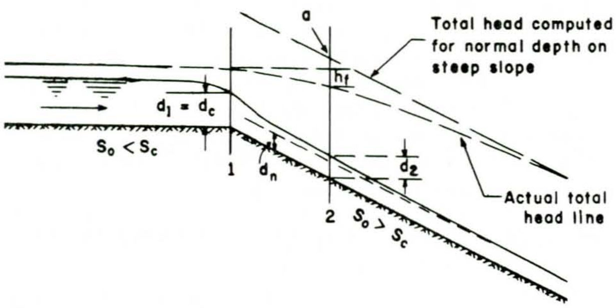


Figure 3.—Water-surface profile in changing from subcritical to supercritical channel slope.

section 1. This is physically impossible, because the total head line must slope downward in the direction of flow. The actual total head line will take the position shown, and have a slope approximately equal to S_c at section 1 and approaching slope S_0 farther downstream. The drop in the total head line h_f between sections 1 and 2 represents the loss in energy due to friction. At section 2 the actual depth d_2 is greater than d_n because sufficient acceleration has not occurred and the assumption of normal depth at this point would clearly be in error. As section 2 is moved downstream, so that total head for normal depth drops below the pool elevation above section 1, the actual depth quickly approaches the normal depth for the steep channel. This type of water surface curve (section 1 to section 2) is characteristically much shorter than the backwater curve discussed in the previous paragraph.

Another common type of nonuniform flow is the drawdown curve to critical depth which occurs upstream from section 1 (fig. 3) where the water surface passes through critical depth. The depth gradually increases upstream from critical depth to normal depth provided the channel remains uniform through a sufficient length. The length of the drawdown curve is much longer than the curve from critical depth to normal depth in the steep channel.

Figure 4 shows a special case for a steep channel discharging into a pool. A hydraulic jump makes a dynamic transition from the supercritical flow in the steep channel to the subcritical flow in the pool. This situation differs from that shown in figure 2 because the flow approaching the pool in figure 4 is supercritical and the total head in the approach channel is large relative to the pool depth. In general, supercritical flow can be changed to subcritical flow only by passing through a hydraulic jump. The violent turbulence in the jump dissipates energy rapidly, causing a sharp drop in the total head line between the supercritical and subcritical states of flow. A jump will occur whenever the ratio of the depth d_1 in the approach channel to the depth d_2 in the downstream channel reaches a specific value. Note in figure 4 that normal depth in the approach channel persists well beyond the point where the projected pool level would intersect the water surface of the channel at normal depth. Normal depth can be assumed to exist on the steep slope upstream from section 1, which is located about at the toe of the jump. More detailed information on the hydraulic jump may be found in textbooks on hydraulics.

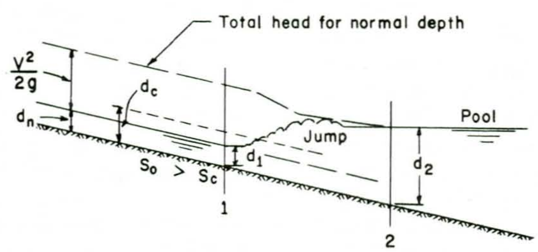


Figure 4.—Water-surface profile illustrating hydraulic jump.

Chapter 3.—RECTANGULAR, TRAPEZOIDAL, AND TRIANGULAR CHANNELS

3.1 Description of Charts. Charts 1–29 are designed for use in the direct solution of the Manning equation for various-sized open channels of rectangular, trapezoidal, and triangular cross section. Each chart (except the triangular cross-section channel chart, No. 29) is prepared for a channel of given bottom width, and having a particular value of Manning's n, but auxiliary scales make the charts applicable to other values of n.

The rectangular cross-section channel charts, Nos. 1–14, are prepared for an n of 0.015 (average value for concrete). A separate chart is provided for each foot of width from 2 feet to 10 feet and for each even foot of width from 10 feet to 20 feet.

The trapezoidal cross-section channel charts, Nos. 15–28, are prepared for an n of 0.03 and side slopes of 2:1 (horizontal to vertical). A separate chart is provided for each foot of bottom width from 2 feet to 10 feet and for each even foot of width from 10 feet to 20 feet. Charts for other side slopes may be constructed according to the method explained in appendix B. Charts for grass-lined channels, where n varies with both depth and type of grass, are given in chapter 4.

The charts for rectangular and trapezoidal cross-section channels are similar in design and method of use. The abscissa scale is discharge, in cubic feet per second (c.f.s.) and the ordinate scale is velocity, in feet per second (f.p.s.). Both scales are logarithmic. Superimposed on the logarithmic grid are steeply inclined lines representing depth (in feet), and slightly inclined lines representing channel slope (in feet per foot). A heavy dashed line on each chart shows the position of critical flow. Auxiliary abscissa and ordinate scales are provided for use with values of n other than those values used in preparing the chart.

In these charts, and subsequent ones similarly designed, interpolations may be made with confidence, not only on the ordinate and abscissa scales, but between the inclined lines representing depth and slope.

The triangular cross-section channel chart, No. 29, is prepared in nomograph form. It may be used for street sections with a vertical (or nearly vertical) curb face. (The curbed street section is a triangular section with one leg vertical.) The equation given on the chart ignores the resistance of the curb face, but this resistance is negligible from a practical viewpoint, provided the width of flow is at least 10 times the depth of the curb face; that is, if $Z>10$. The equation gives a discharge about 19 percent greater than will be obtained by the common procedure of computing discharge from the hydraulic radius of the entire section. The latter procedure is not recommended for shallow flow with continuously varying depth. The nomograph may also be used for shallow V-shaped sections by following the instructions on the chart.

3.2 General instructions for use of charts 1–28. Charts 1–28 provide a solution of the Manning equation for flow in open channels of uniform slope, cross section, and roughness, provided the flow is not affected by backwater and the channel has a length sufficient to establish uniform flow. The charts provide accuracy sufficient for the design of highway drainage channels of fairly uniform cross section and slope. Rounding of the intersection of the side slopes with the bottom of the channel does not appreciably affect the channel capacity.

The charts may also be used to obtain rough approximations for depths and velocities in natural channels of nearly the nominal cross section. For such channels, a straight line drawn through irregularities in the bed profile may be used to define the slope. The rectangular cross-section charts can be used for closed rectangular conduits flowing full, by following the procedure described in section 3.2–3.

The use of charts 1–28 is described, with examples, in the following subsections. Instructions and example for chart 29 are given on the chart itself.

3.2–1 Use of charts 1–28 with basic chart-design value of *n*. For a given slope and cross section of channel, when n is 0.015 for rectangular channels or 0.03 for trapezoidal channels, the depth and velocity of uniform flow may be read directly from the chart for that size channel. The initial step is to locate the intersection of a vertical line through the discharge (abscissa) and the appropriate slope line. At this intersection, the depth of flow is read from the depth lines; and the mean velocity is read on the ordinate scale opposite the point of intersection (see examples 1 and 2). The procedure is reversed to determine the discharge at a given depth of flow (see example 3). Critical depth, slope, and velocity for a given discharge can be read on the appropriate line or scale (velocity) at the intersection of the critical curve and a vertical line through the discharge.

Example 1

Given: A rectangular concrete channel 5 ft. wide, with $n=0.015$, on a 1-percent slope ($S=0.01$), discharging 200 c.f.s. *Find:* Depth, velocity, and type of flow.

1. Select the rectangular chart for a 5-ft. width, chart 4.
2. From 200 c.f.s. on the Q scale, move vertically to intersect the slope line $S=0.01$, and from the depth lines read $d_n=3.2$ ft.
3. Move horizontally from the same intersection and read the normal velocity, $V=12.5$ f.p.s., on the ordinate scale.
4. The intersection lies above the critical curve, and the flow is therefore in the supercritical range.

Example 2

Given: A trapezoidal channel with 2:1 side slopes and a 4-ft. bottom width, with $n=0.030$, on a 2-percent slope ($S=0.02$), discharging 150 c.f.s. *Find:* Depth, velocity, and type of flow.

1. Select the trapezoidal chart for $b=4$ ft., chart 17.
2. From 150 c.f.s. on the Q scale, move vertically to intersect the slope line $S=0.02$, and from the depth lines read $d_n=2.1$ ft.
3. Move horizontally from the same intersection and read the normal velocity, $V=8.4$ f.p.s., on the ordinate scale.
4. The intersection lies above the critical curve, and the flow is therefore in the supercritical range.

Example 3

Given: A trapezoidal channel with 2:1 side slopes, a 6-ft. bottom width, and a depth of 4.0 ft., with $n=0.030$, on a 0.5-percent slope ($S=0.005$). *Find:* Discharge, velocity, and type of flow.

1. Select the trapezoidal chart for $b=6$ ft., chart 19.
2. Locate the intersection of the 4-ft. depth line and the slope line $S=0.005$ and, moving vertically to the abscissa scale, read the corresponding discharge, $Q=350$ c.f.s.
3. Move horizontally from the intersection and read the normal velocity, $V=6.1$ f.p.s., on the ordinate scale.
4. The intersection lies below the critical curve, and the flow is therefore in the subcritical range.

3.2–2 Use of charts 1–28 with other than basic chart-design value of *n*. Auxiliary scales, labeled Qn (abscissa) and Vn (ordinate), are provided on charts 1–28 so that the charts may be used for values of n other than those for which the charts were basically prepared. To use the auxiliary scales, multiply the discharge by the value of n and use the Qn and Vn scales instead of the Q and V scales, except for computation of critical depth or critical velocity (see step 5 of example 4). To obtain normal velocity V from a value on the Vn scale, divide the value by n (see example 4).

Example 4

Given: A rectangular cement rubble masonry channel 5 ft. wide, with $n=0.025$, on a 1.5-percent slope ($S=0.015$), discharging 200 c.f.s. *Find:* Depth, velocity, and type of flow.

1. Select the rectangular chart for a 5-ft. width, chart 4.
2. Multiply Q by n to obtain Qn: $200\times 0.025=5.00$.
3. From 5.00 on the Qn scale, move vertically to intersect the slope line, $S=0.015$, and at the intersection read $d_n=4.1$ ft.
4. Move horizontally from the intersection and read $Vn=0.24$ on the Vn scale. The normal velocity $V=Vn/n=0.24\div 0.025=9.6$ f.p.s.
5. Critical depth and critical velocity are independent of the value of n and their values can be read at the intersection of the critical curve with a vertical line through the discharge. For 200 c.f.s., on chart 4, $d_c=3.7$ ft. and $V_c=10.8$ f.p.s. The normal velocity, 9.6 f.p.s. (from step 4), is less than the critical velocity, and the flow is therefore subcritical. It will also be noted that the normal depth, 4.1 ft., is greater than the critical depth, 3.7 ft., which is also an indication of subcritical flow.
6. To determine the critical slope for $Q=200$ c.f.s. and $n=0.025$, start at the intersection of the critical curve and a vertical line through the discharge, $Q=200$ c.f.s., finding d_c (3.7 ft.) at this point. Follow along this d_c line to its intersection with a vertical line through $Qn=5.00$ (step 2), and at this intersection read the slope value $S_c=0.019$.

3.2–3 Closed rectangular conduits flowing full. Charts 1–14 may be used to compute the friction slope S_f of rectangular conduits flowing full, provided the discharge is adjusted to allow for the increased resistance caused by friction against the top of the box (conduit). This adjustment is made by multiplying Q (or Qn) by a factor equal to the two-thirds power of the ratio of (1) the hydraulic radius of an open channel of depth equal to D, the height of the box, to (2) the hydraulic radius of the box, flowing full. This may be reduced to the expression:

$$\text{factor for } Q=\left(\frac{2B+2D}{B+2D}\right)^{2/3}$$

where B=span or width of box and D=height of box.

To facilitate making the adjustment of Q, the factors shown in table 4 (see p. 101) have been computed for use (intermediate values may be interpolated).

Having determined the factor for Q, enter the channel chart having the proper bottom width with the adjusted Q, equal to the design Q (or Qn) multiplied by the proper factor, and read the friction slope S_f at the point where the vertical line through the adjusted Q (or Qn) intersects the depth line which equals the height of the box (see example 5).

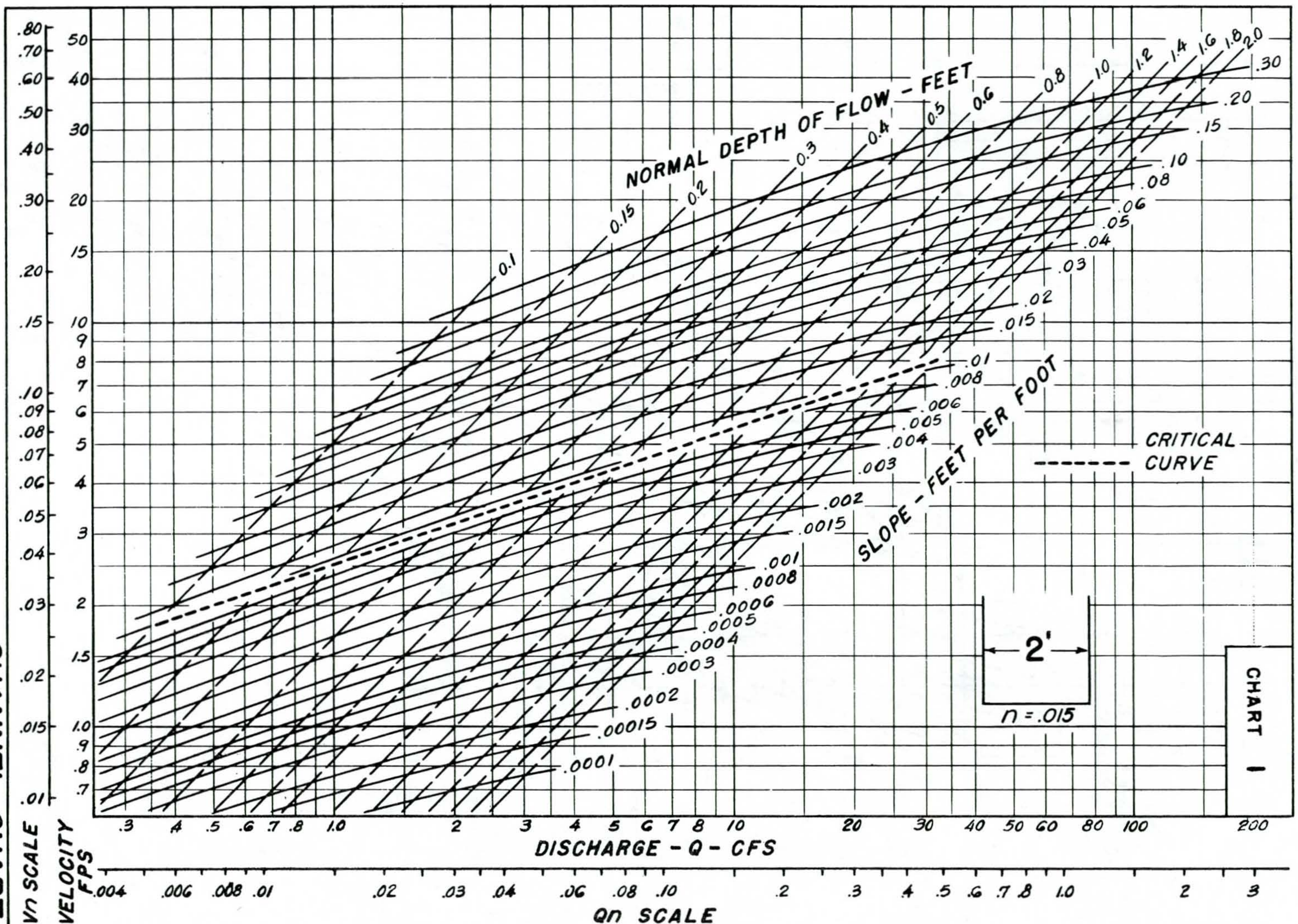
The slope of the pressure line (which equals S_f) for a conduit flowing full is independent of the slope of the conduit. The mean velocity in the conduit may be computed from the formula $V=Q/A$ or it may be read directly from the chart opposite the point where a vertical line through the design Q intersects the depth line which equals the height of the conduit.

Example 5

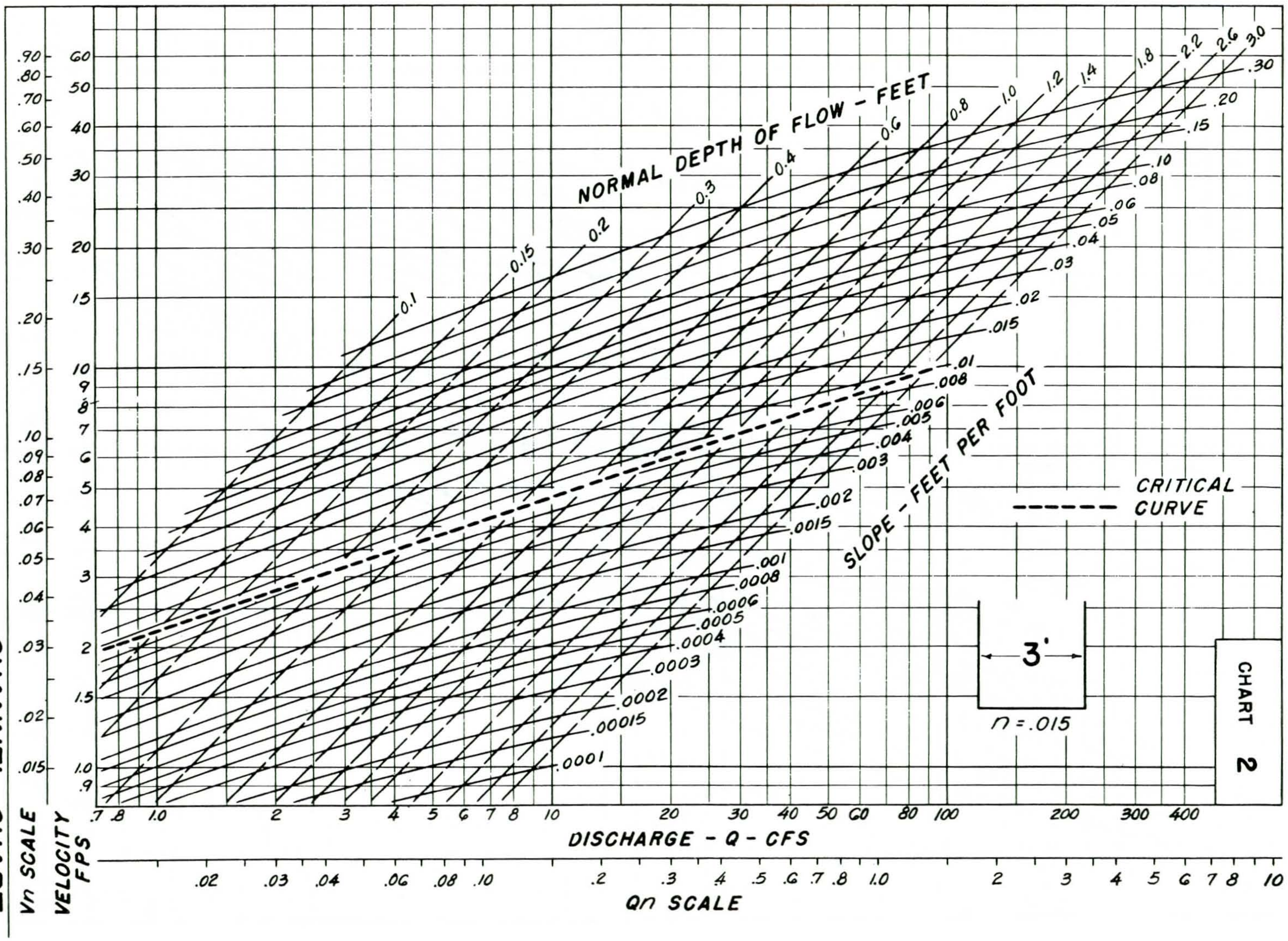
Given: A rectangular concrete box conduit 6 ft. wide by 4 ft. high, with $n=0.015$, on a slope $S=0.0010$, discharging 150 c.f.s. *Find:* Whether the box flows full or part full and, if full, the slope of the energy line (friction slope S_f).

1. Select the rectangular cross-section chart for 6-ft. width, chart 5.
2. At the intersection of $Q=150$ c.f.s. and $S=0.0010$, read $d_n=5.2$ ft. This depth, required for normal flow, exceeds the available depth of 4.0 ft.; thus the conduit must flow full at a discharge of 150 c.f.s.
3. The D/B ratio$=4/6=0.667$. From table 4, the corresponding factor is 1.27.
4. The adjusted $Q=1.27\times 150=190$ c.f.s.
5. On chart 5 ($B=6$ ft.), at the intersection of a vertical line through $Q_{adj.}=190$ c.f.s. and the depth line for $D=4.0$ ft., read the friction slope $S_f=0.0031$. The slope of the energy line is steeper than the bed slope, 0.0010.
6. The mean velocity, 6.2 c.f.s., can be read on chart 5, moving across from the intersection of $Q=150$ c.f.s. and $D=4.0$ ft.; or it may be calculated as $V=150\div(6\times 4)=6.2$ c.f.s.

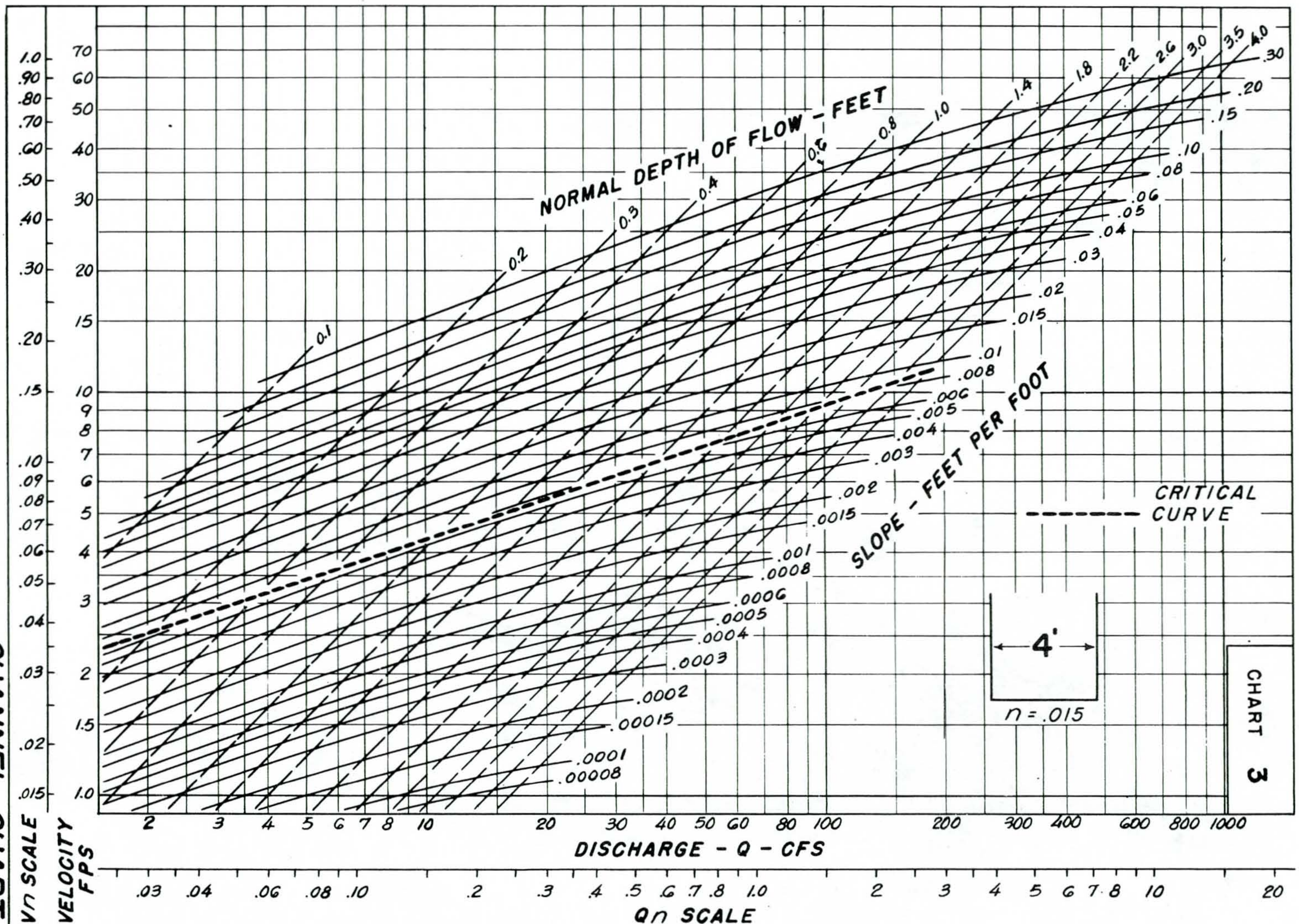
CHANNEL CHART
VERTICAL b = 2 FT.



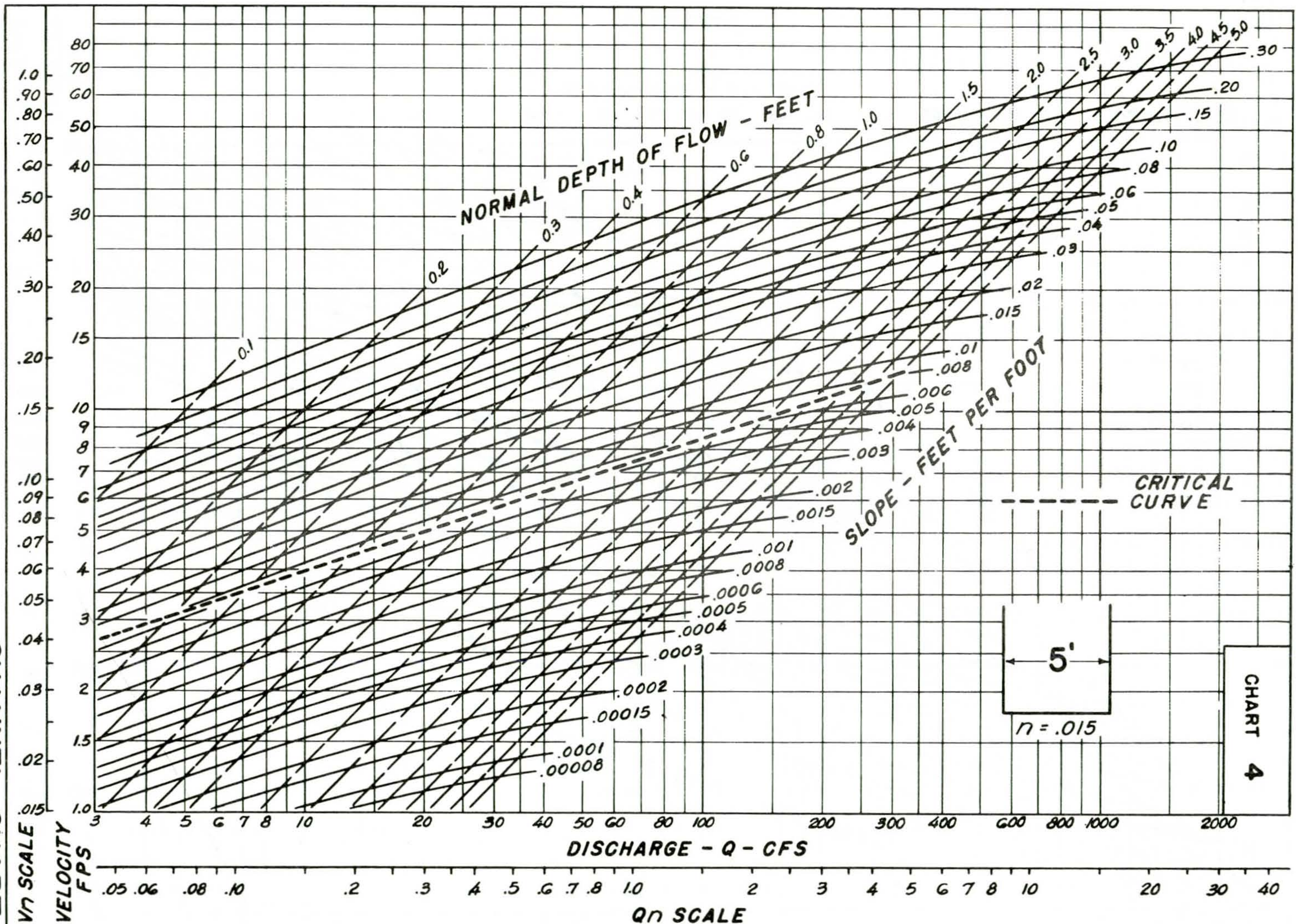
CHANNEL CHART VERTICAL b = 3 FT.

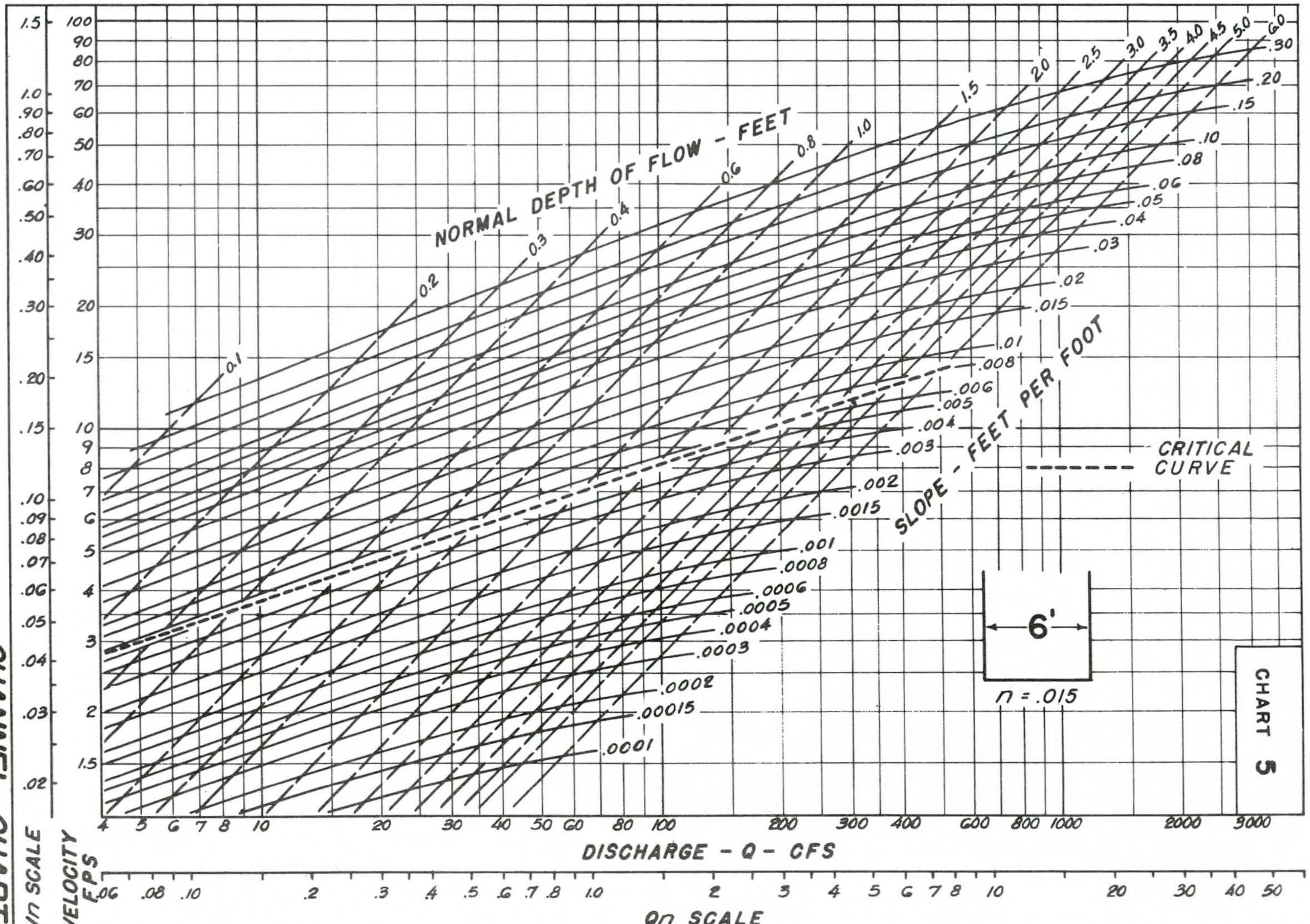


CHANNEL CHART
VERTICAL b = 4 FT.



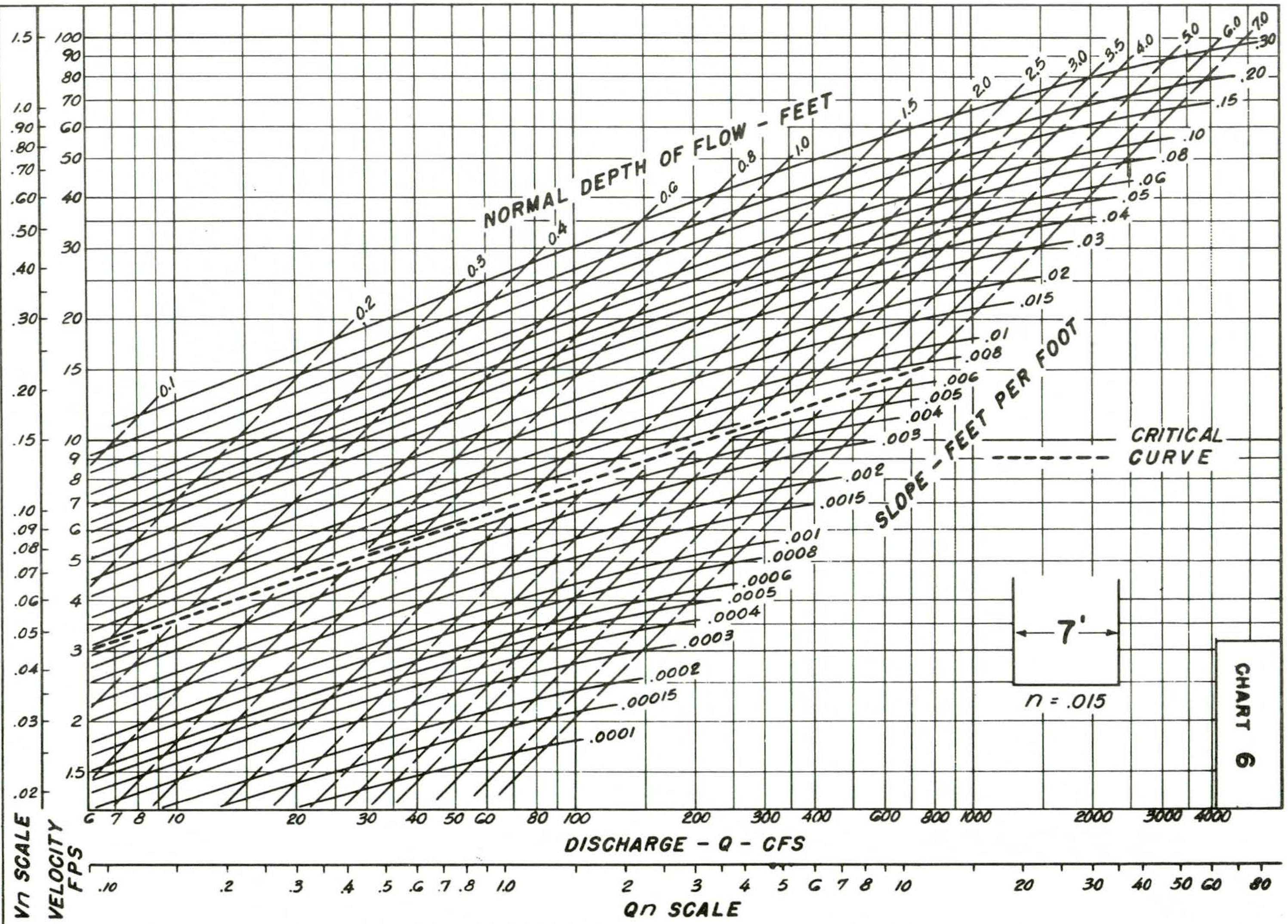
CHANNEL CHART
VERTICAL b = 5 FT.



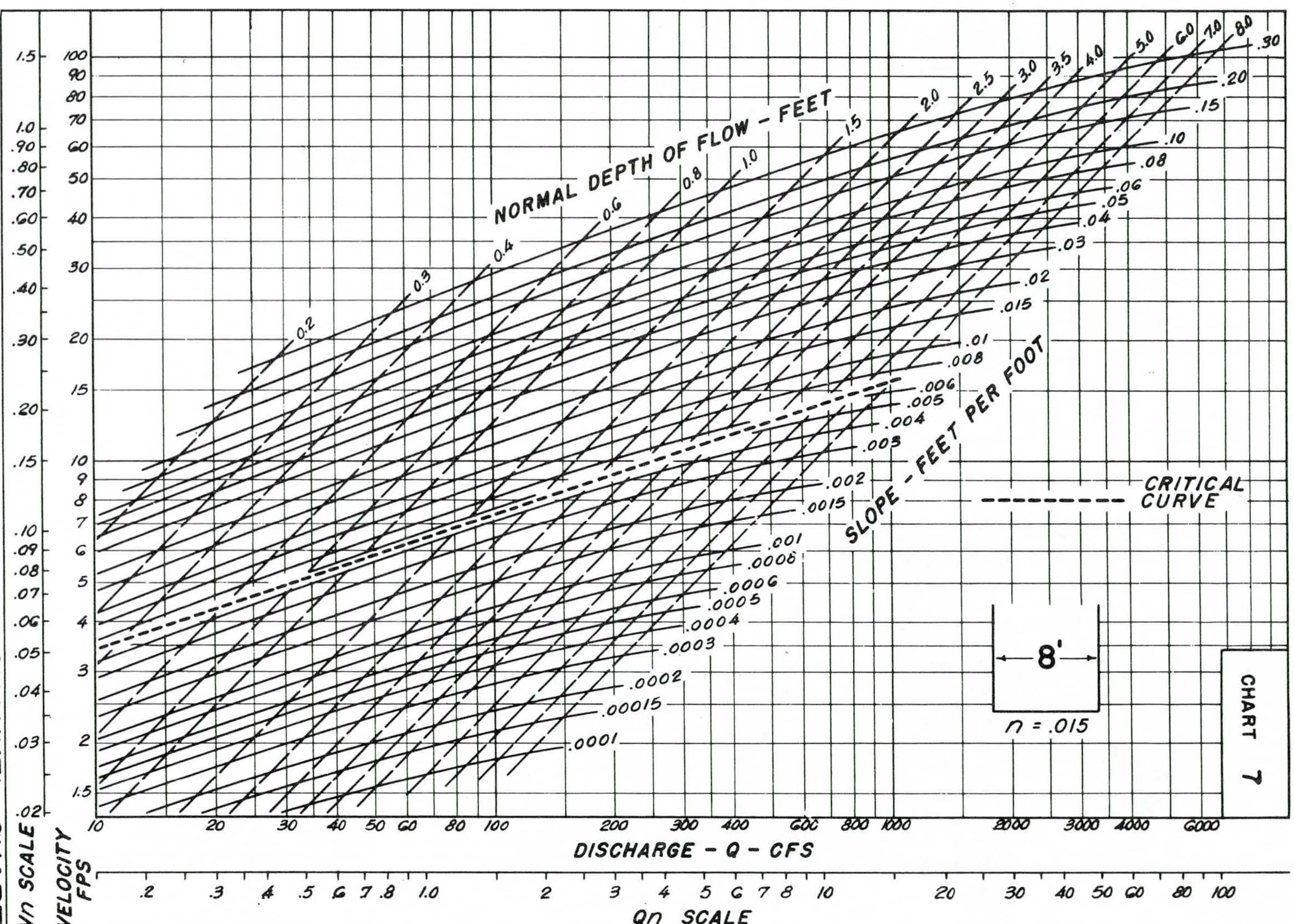


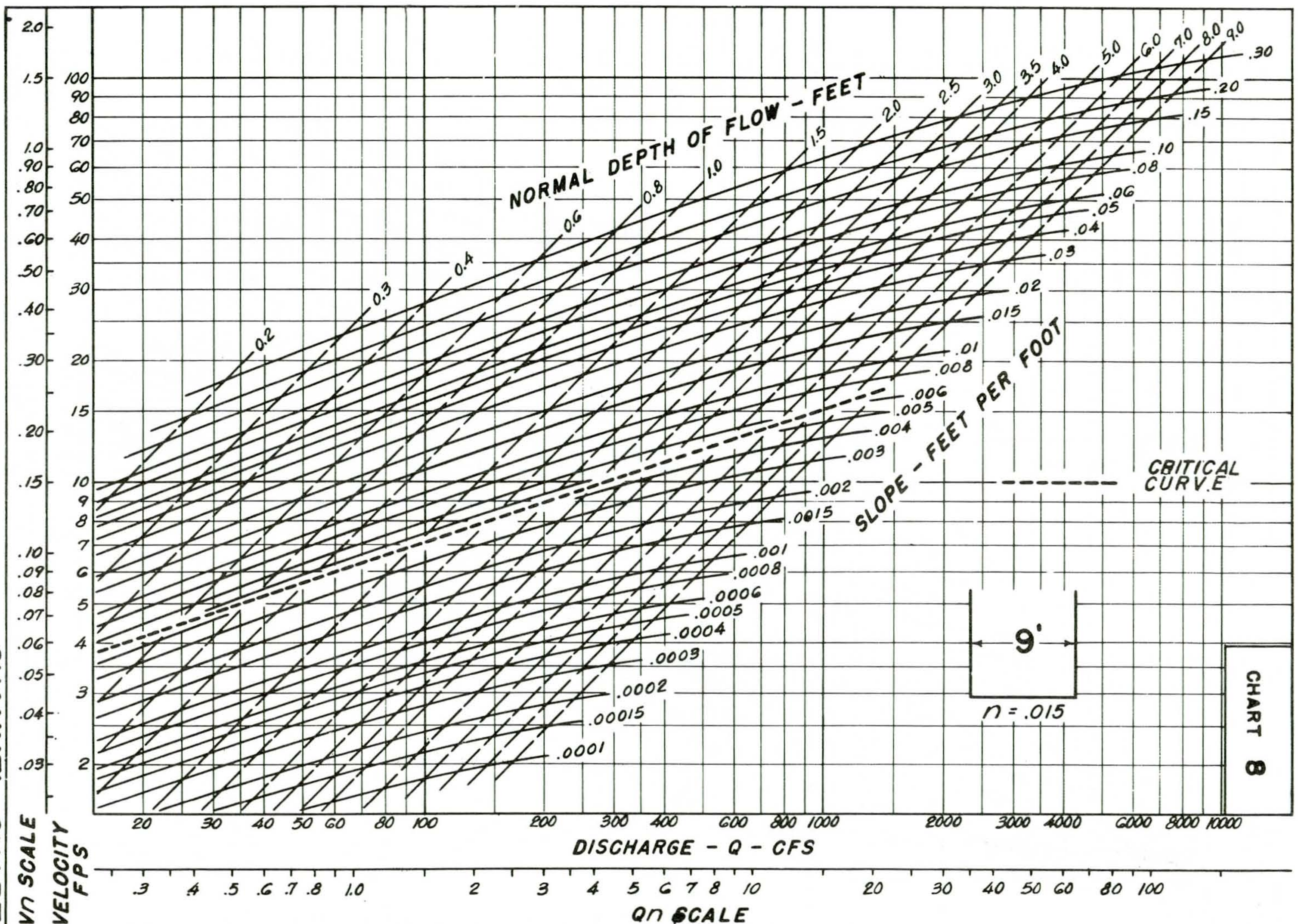
CHANNEL CHART
VERTICAL b = 6 FT.

CHANNEL CHART
VERTICAL b = 7 FT.



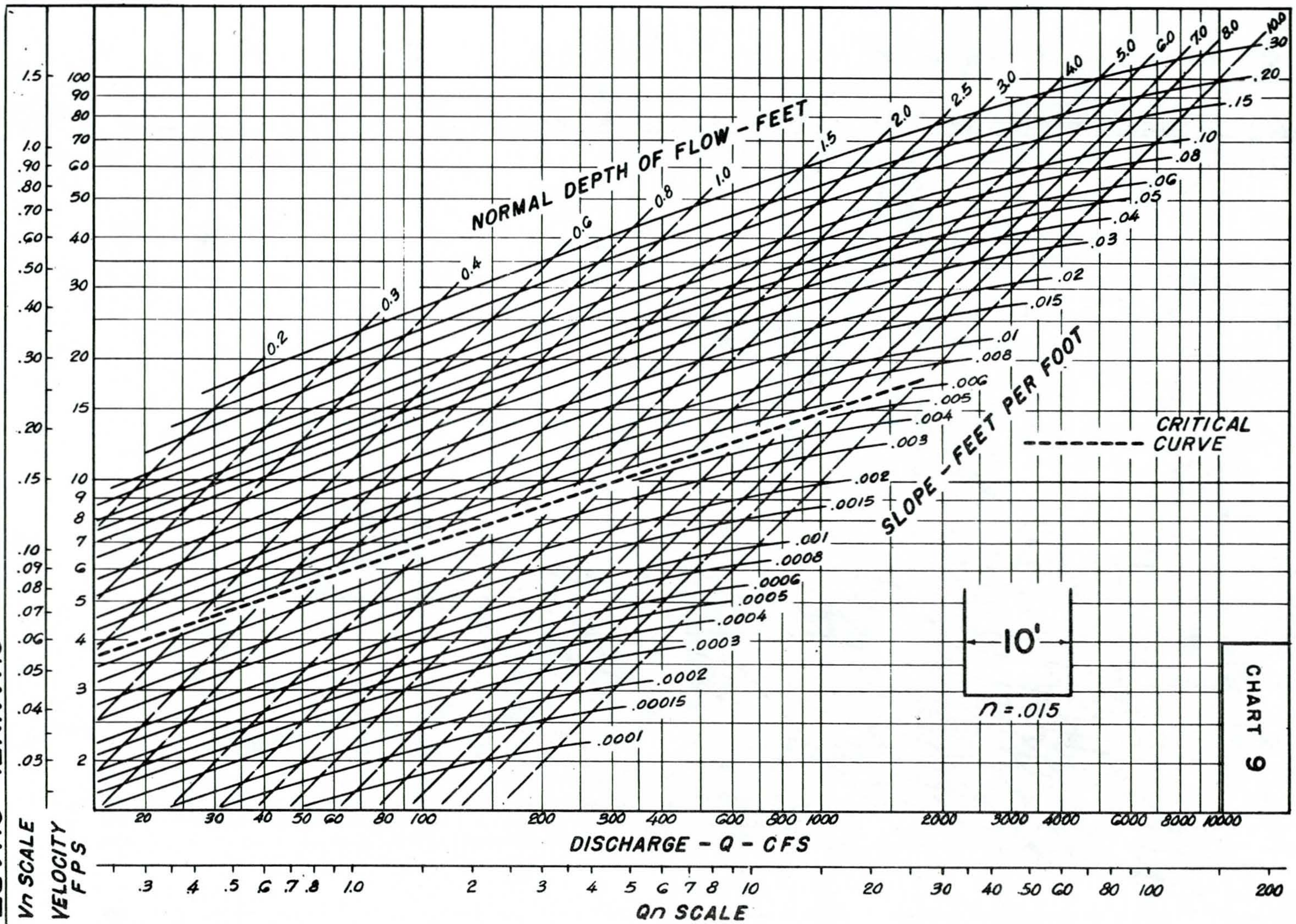
CHANNEL CHART
VERTICAL b = 8 FT.



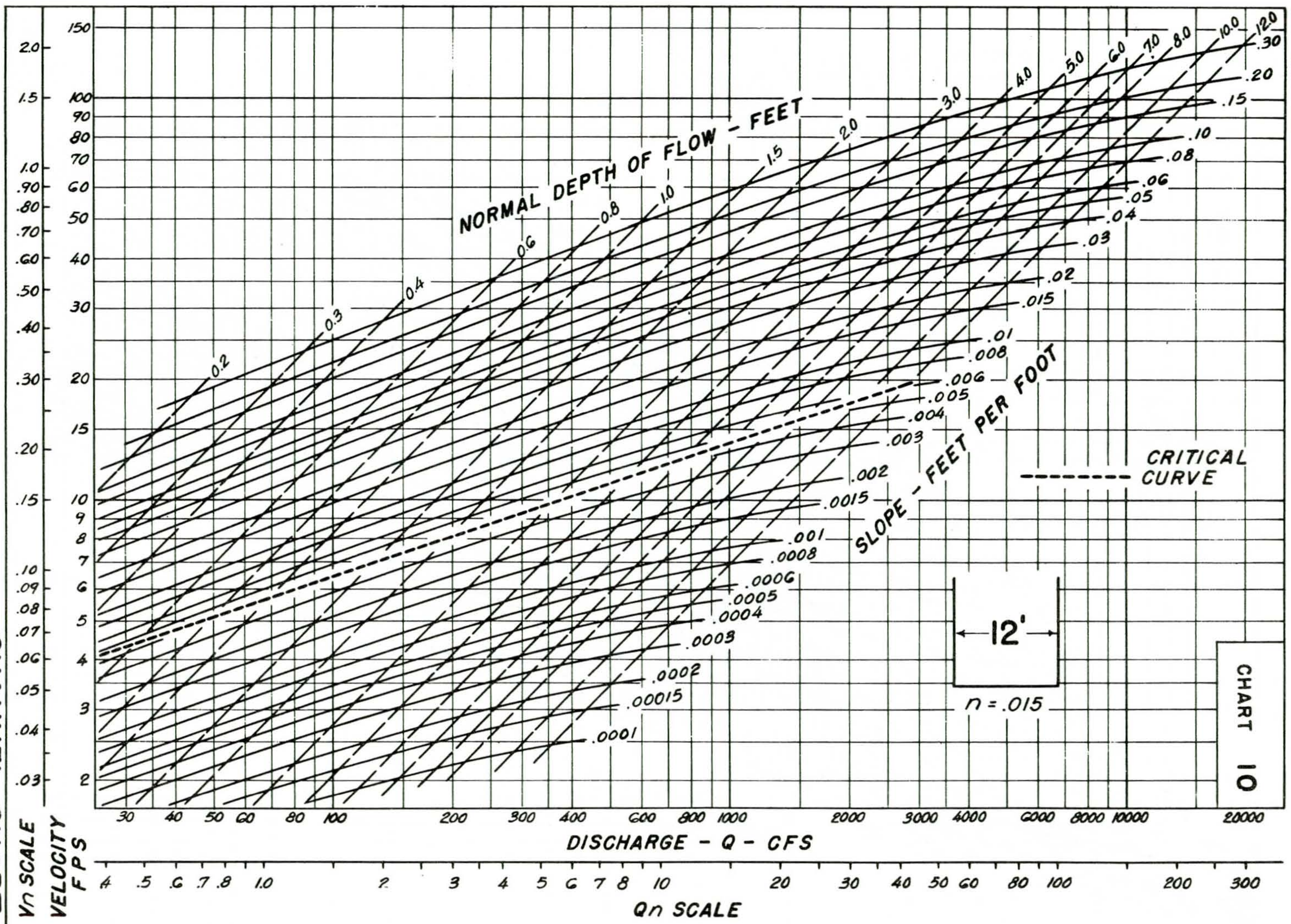


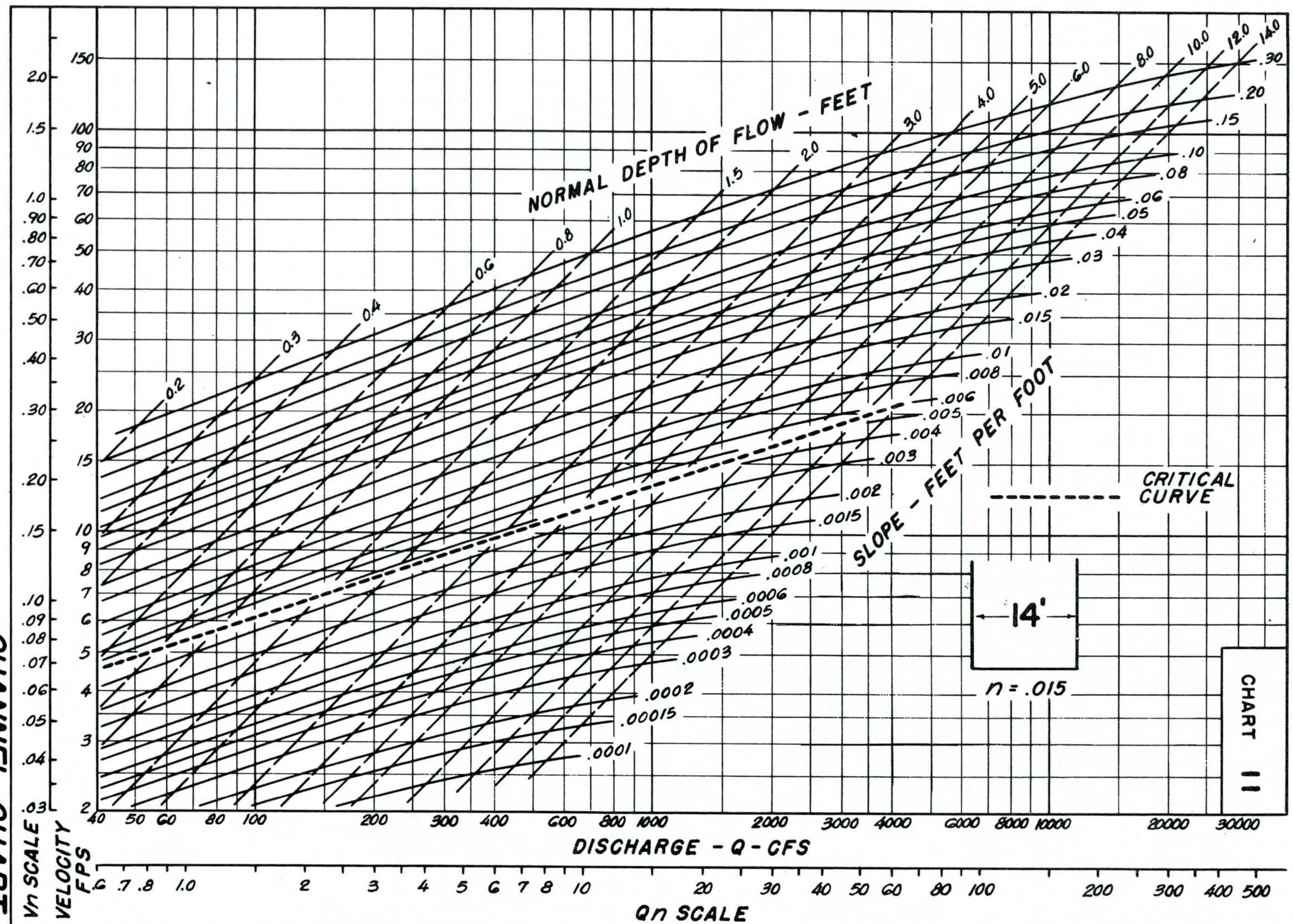
CHANNEL CHART
VERTICAL b = 9 FT.

CHANNEL CHART
VERTICAL b = 10 FT.

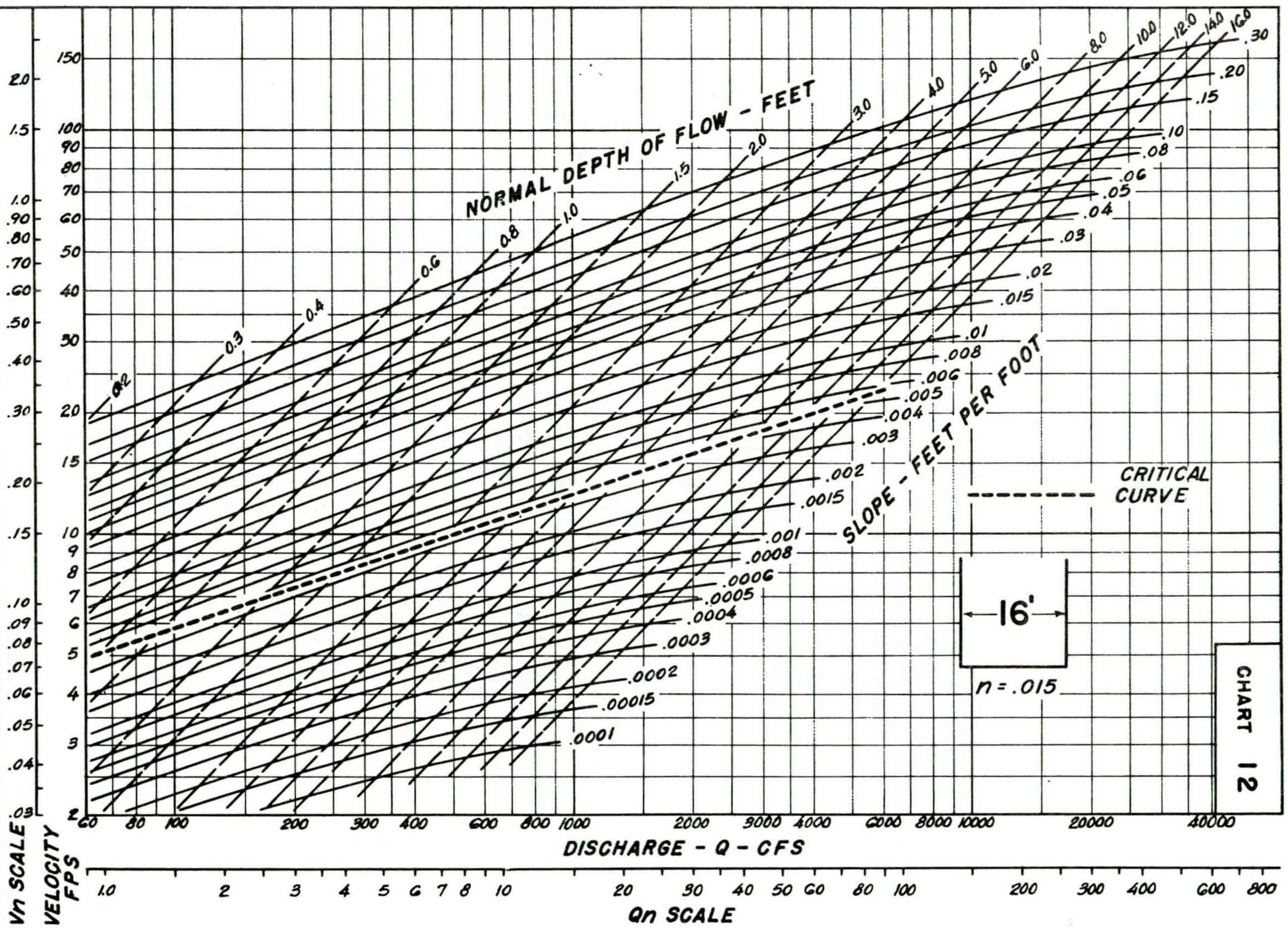


CHANNEL CHART
VERTICAL b = 12 FT.





CHANNEL CHART
VERTICAL b = 14 FT.



CHANNEL CHART
VERTICAL b = 16 FT.

CHANNEL CHART
VERTICAL b = 18 FT.

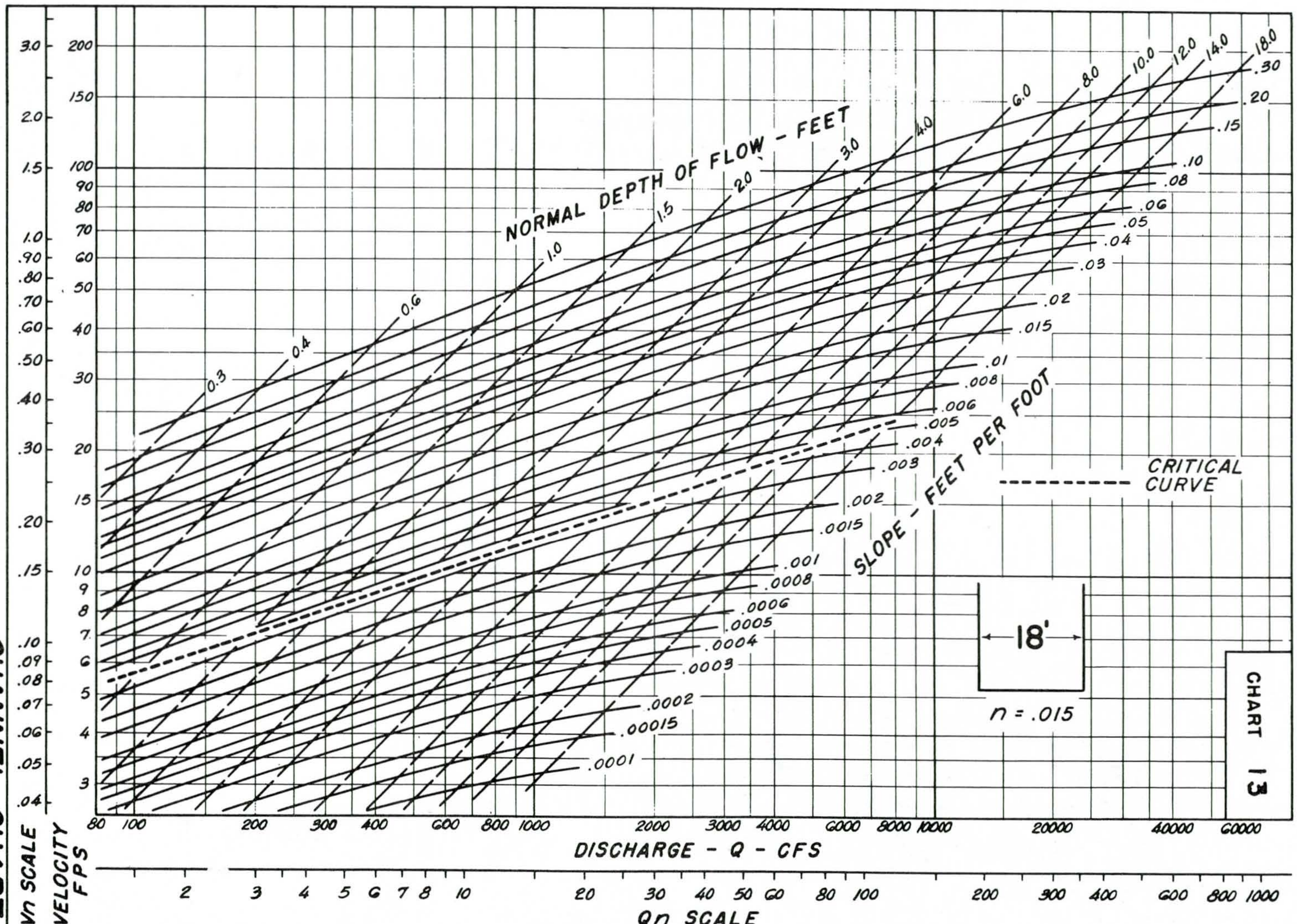
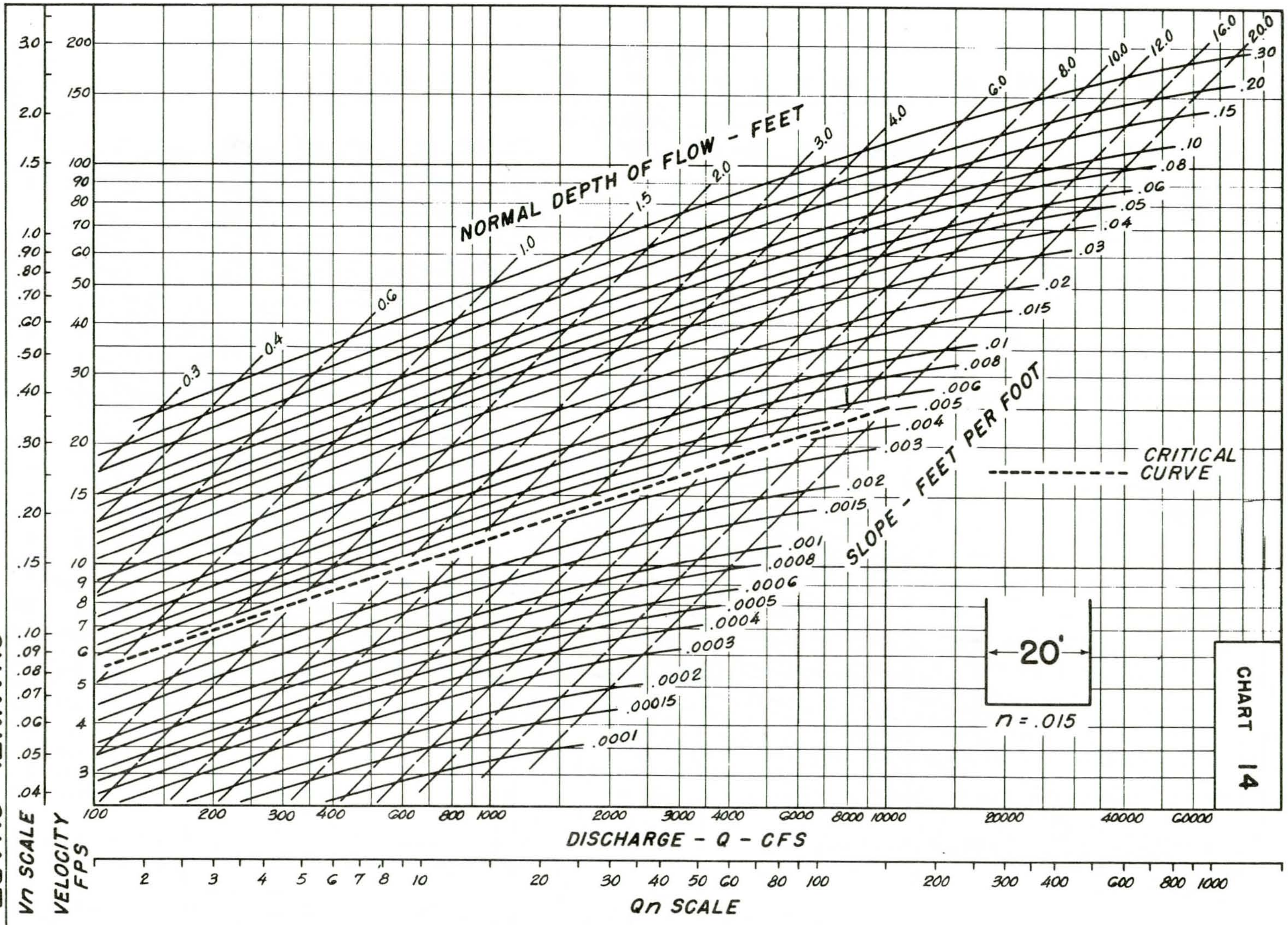
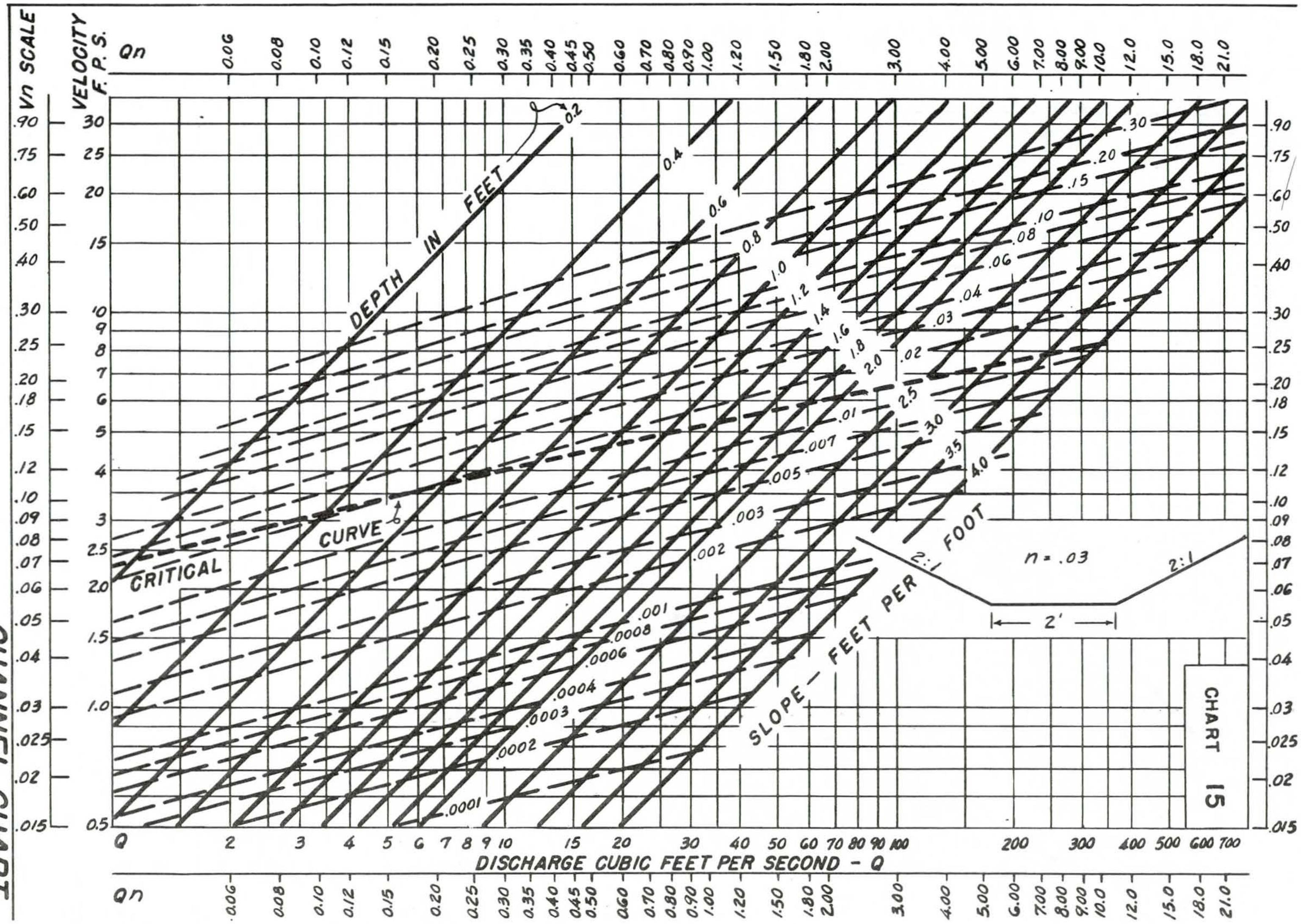


CHART 13

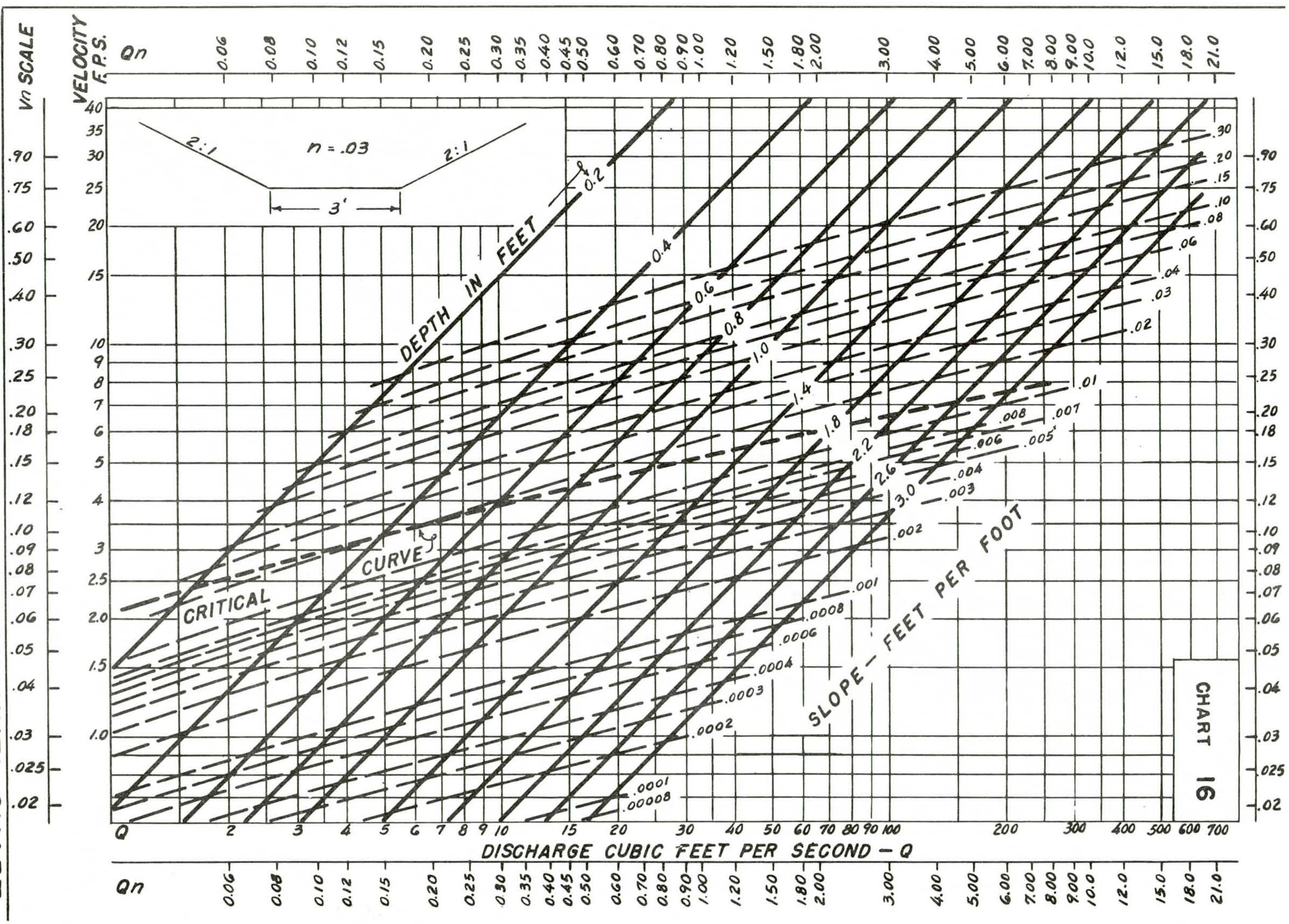
CHANNEL CHART
VERTICAL b = 20 FT.

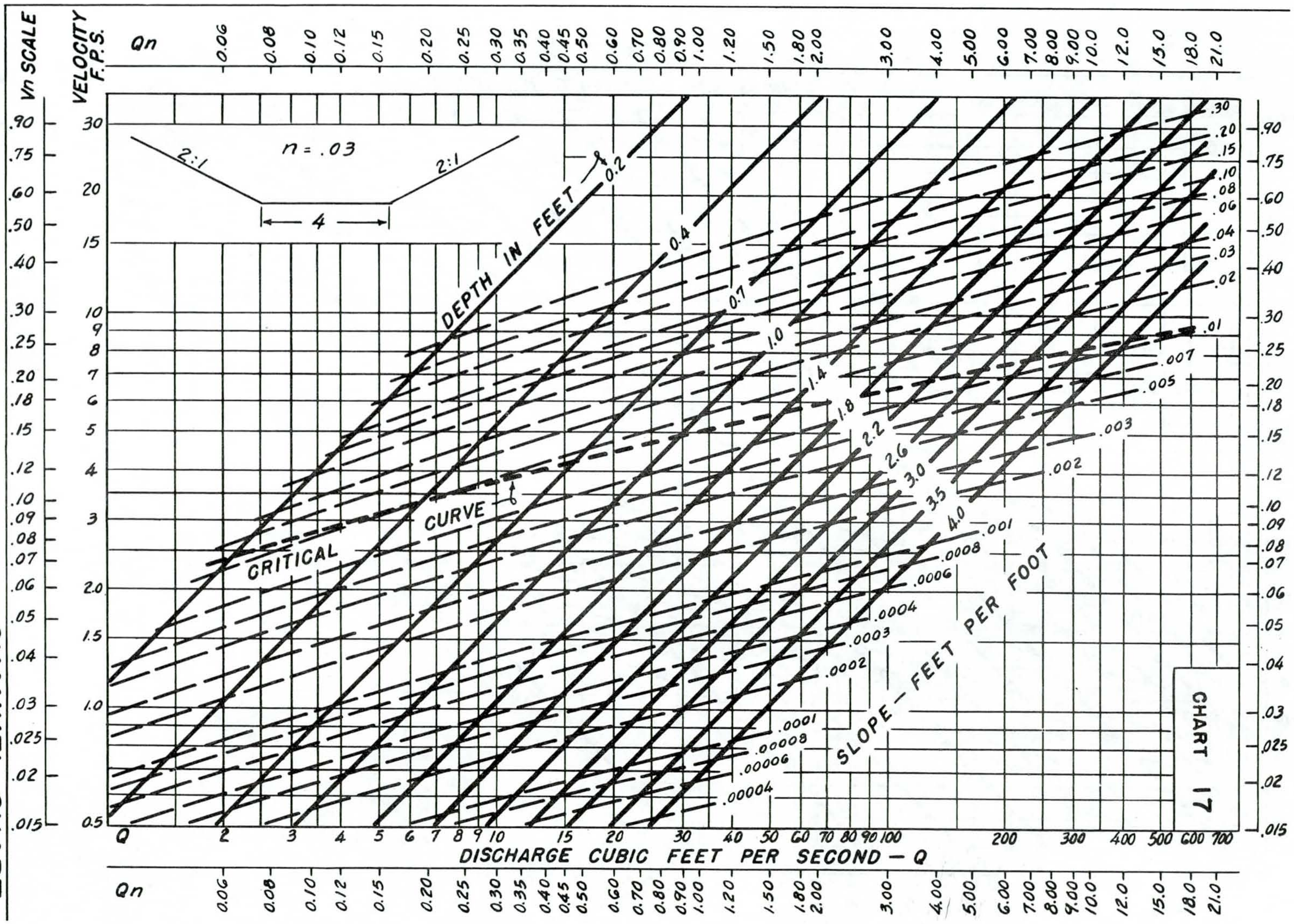


CHANNEL CHART
2:1 b = 2 FT.



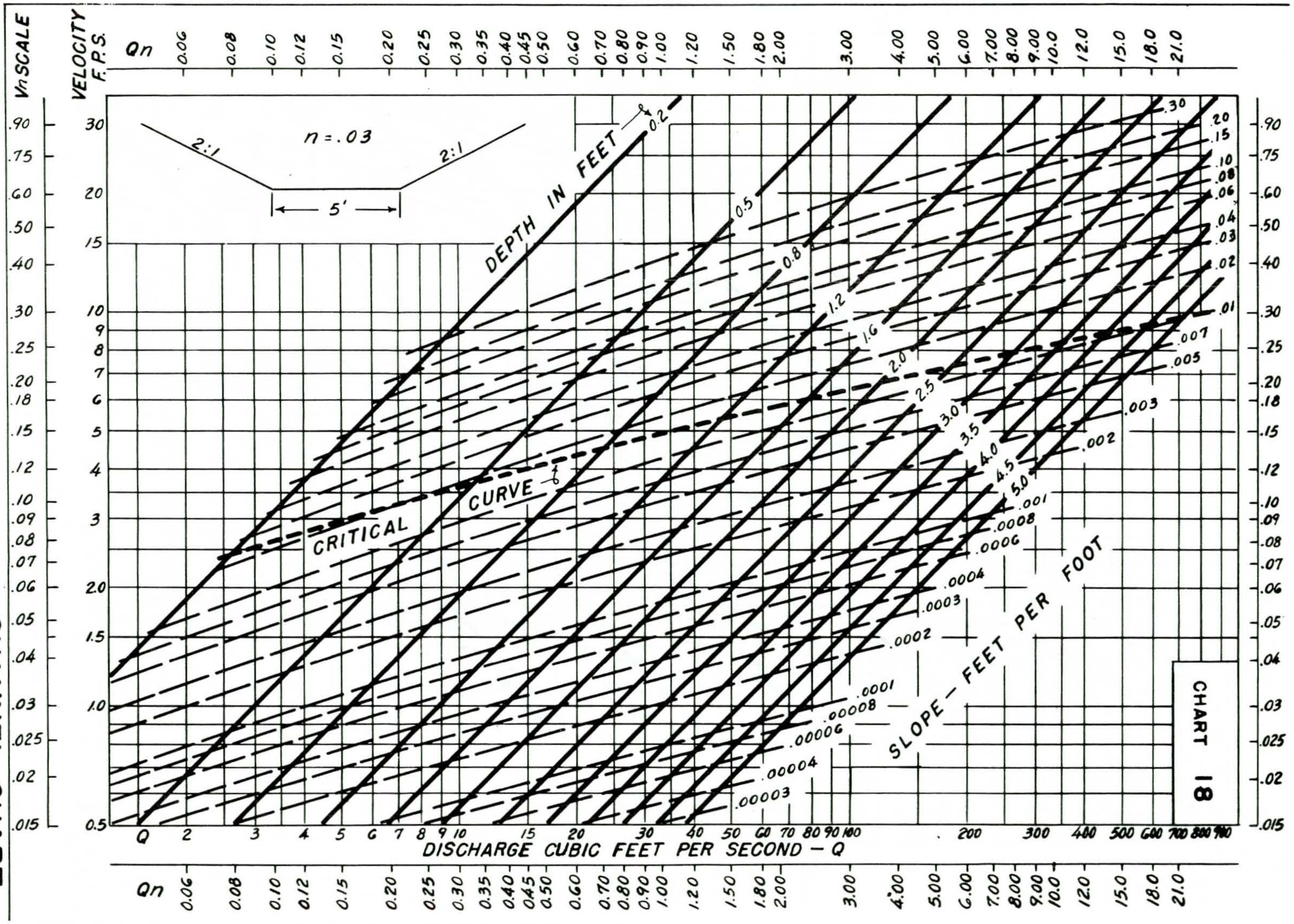
CHANNEL CHART
2:1 b = 3 FT.

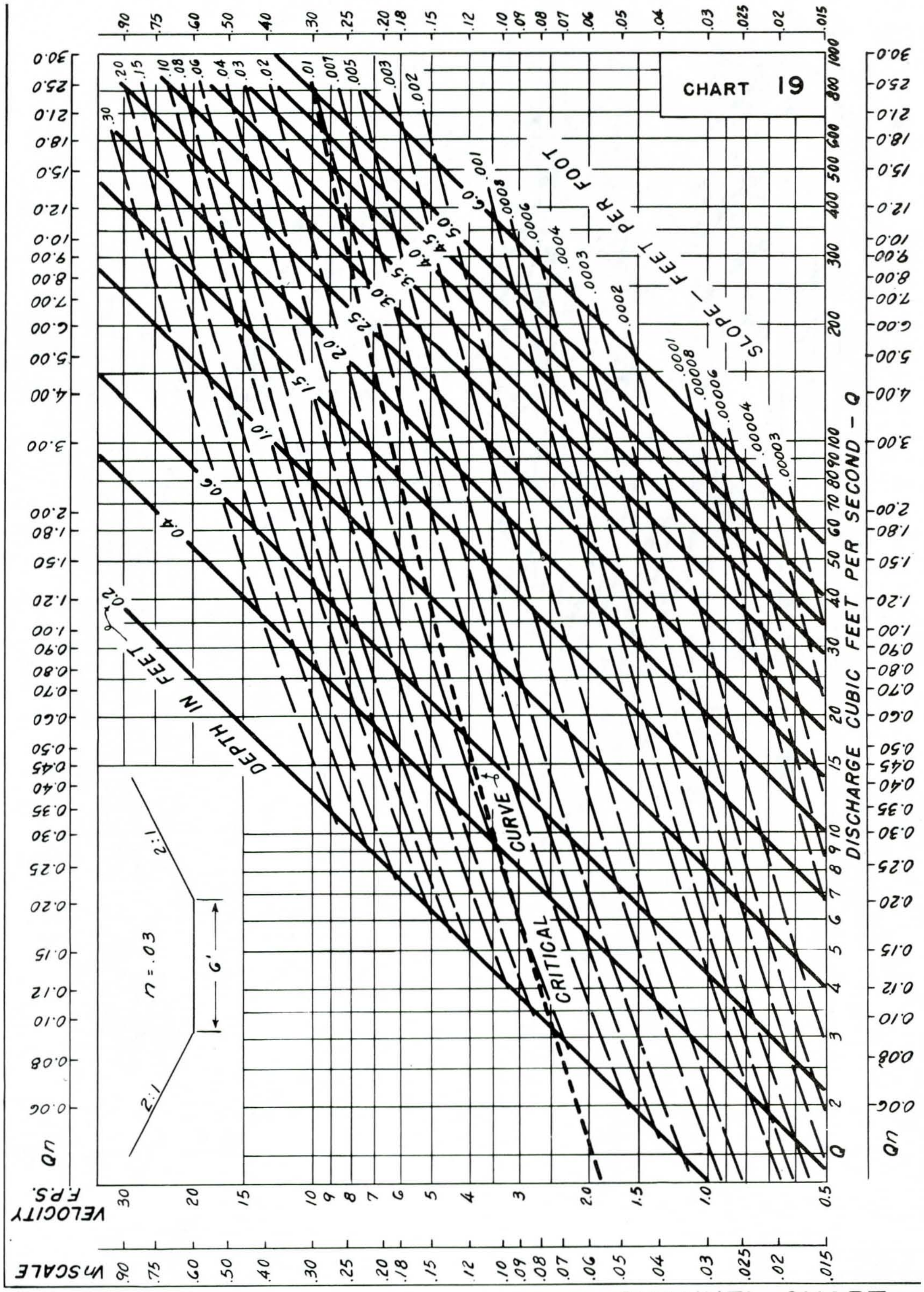




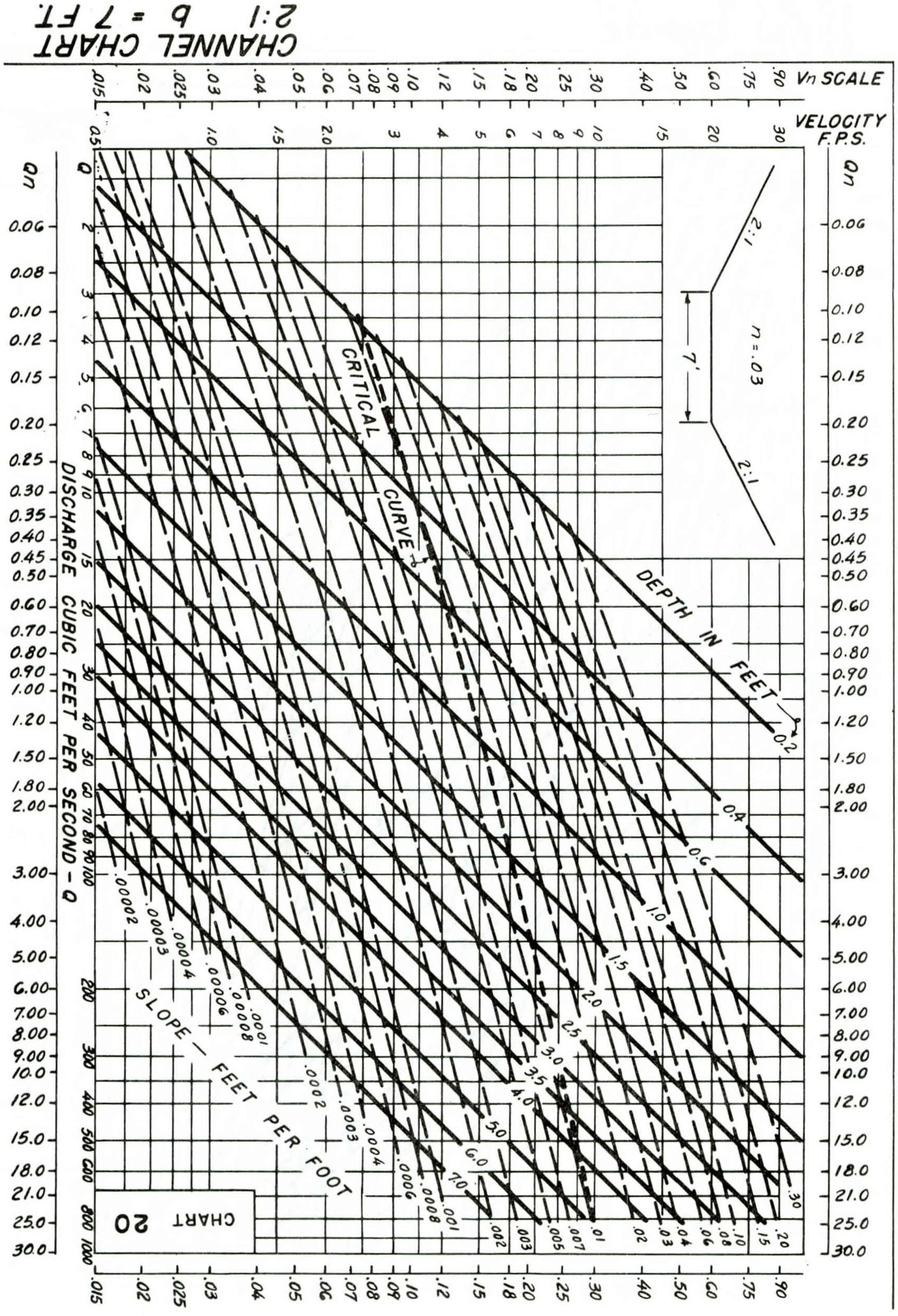
CHANNEL CHART
2:1 b = 4 FT.

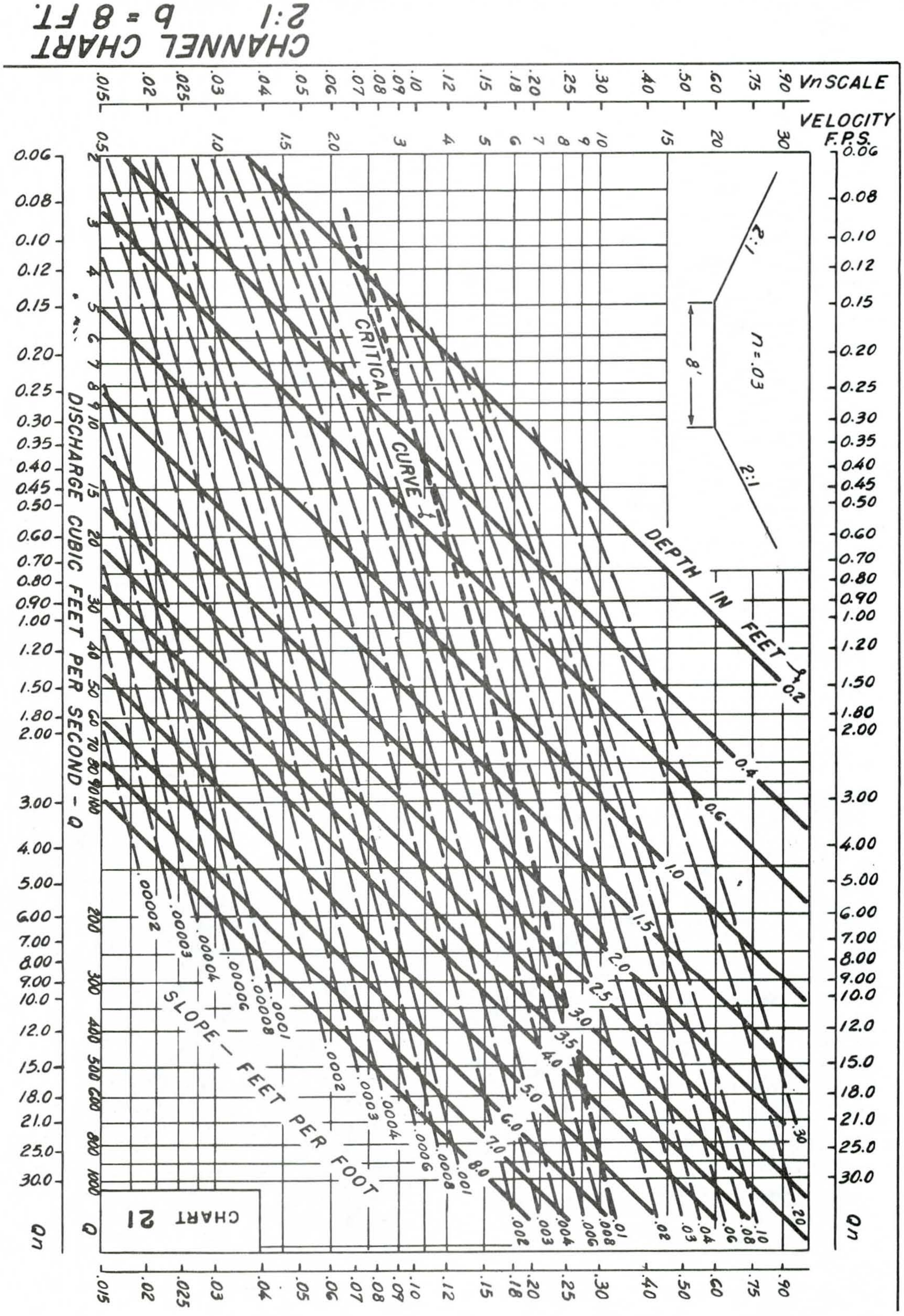
CHANNEL CHART
2:1 b = 5 FT.

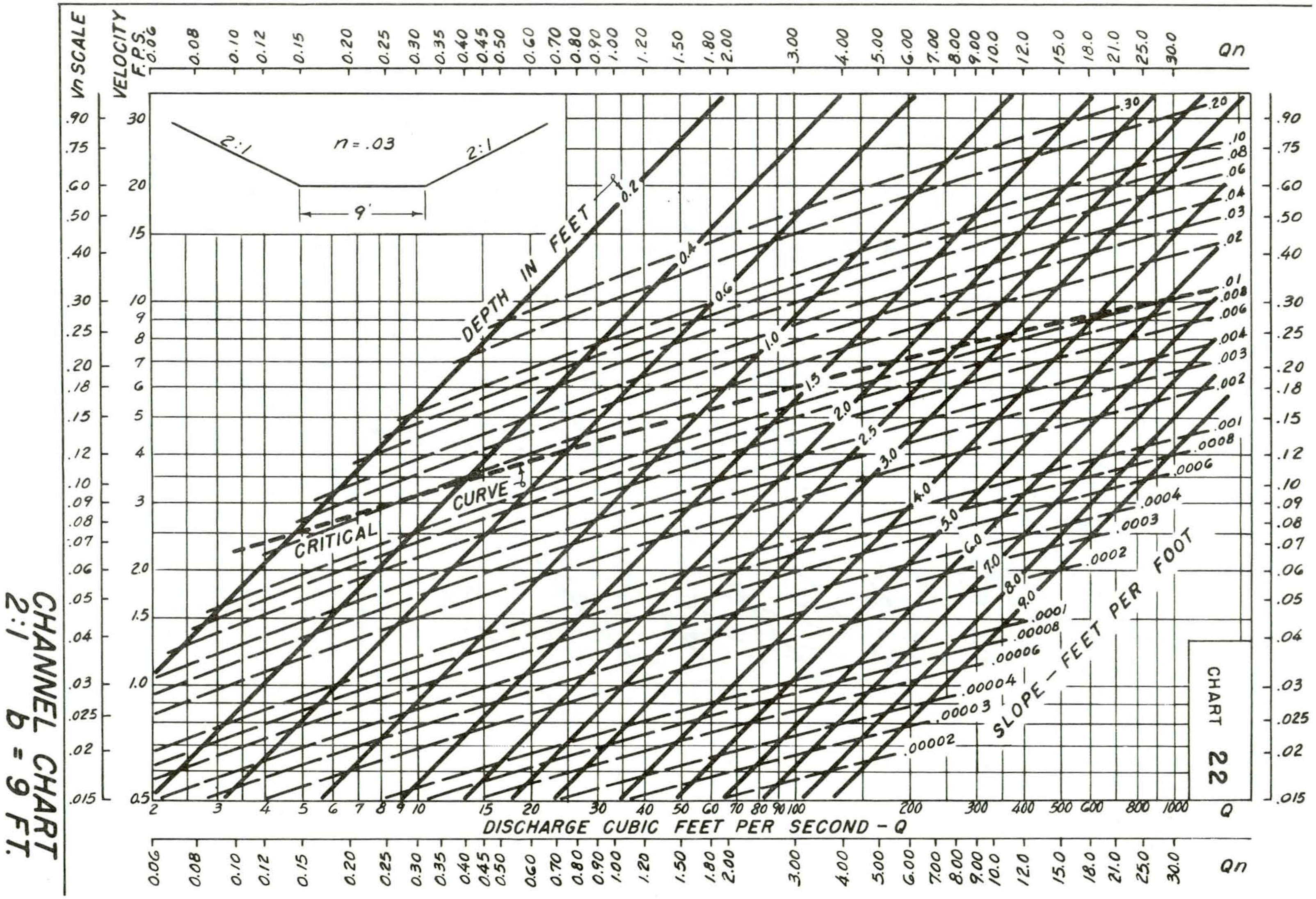




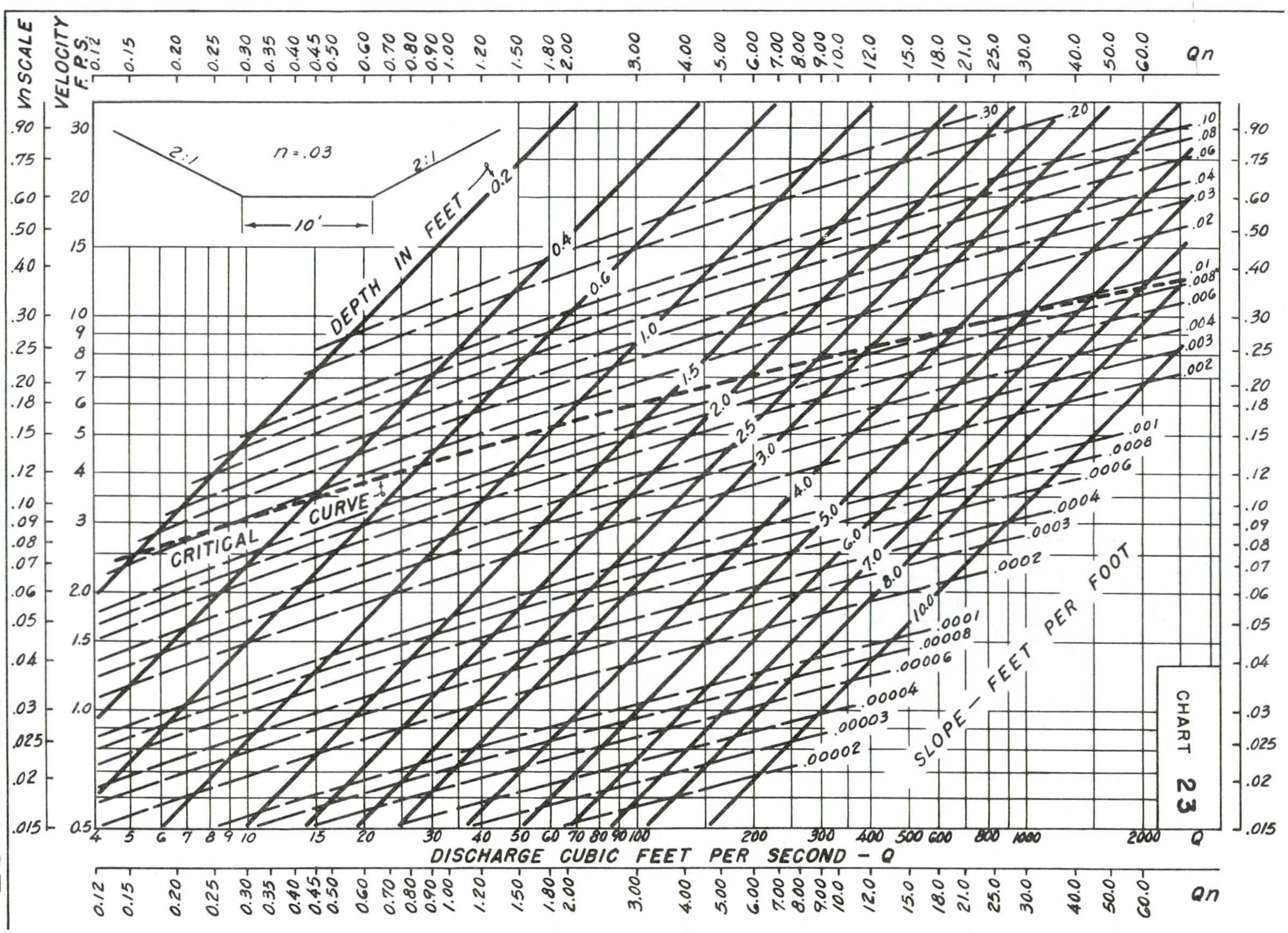
CHANNEL CHART
2:1 b = 6 FT.

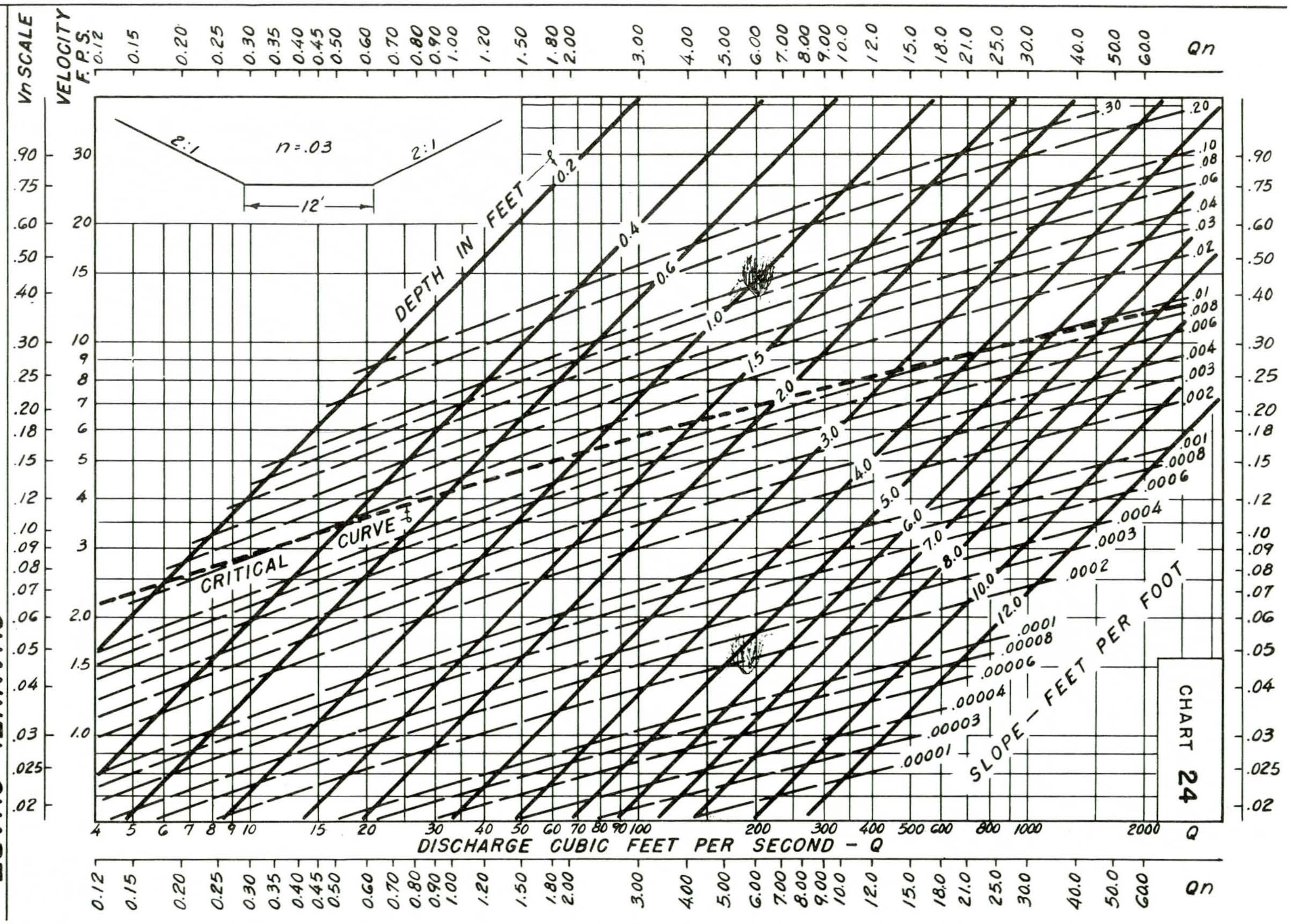

CHANNEL CHART
2:1 b = 7 FT.
Vn SCALE
VELOCITY F.P.S.
Qn
Q
DISCHARGE CUBIC FEET PER SECOND – Q
CRITICAL CURVE
DEPTH IN FEET
SLOPE — FEET PER FOOT
n = .03
7'
2:1
CHART 20


CHANNEL CHART
2:1 b = 8 FT.
Vn SCALE
VELOCITY F.P.S.
DISCHARGE CUBIC FEET PER SECOND - Q
CRITICAL CURVE
DEPTH IN FEET
SLOPE — FEET PER FOOT
n = .03
8'
2:1
Qn
Q
CHART 21


CHANNEL CHART
2:1 b = 9 FT.
CHART 22
n = .03
2:1
2:1
9'
Vn SCALE
VELOCITY F.P.S.
Qn
DEPTH IN FEET
CRITICAL CURVE
SLOPE - FEET PER FOOT
DISCHARGE CUBIC FEET PER SECOND - Q
Q

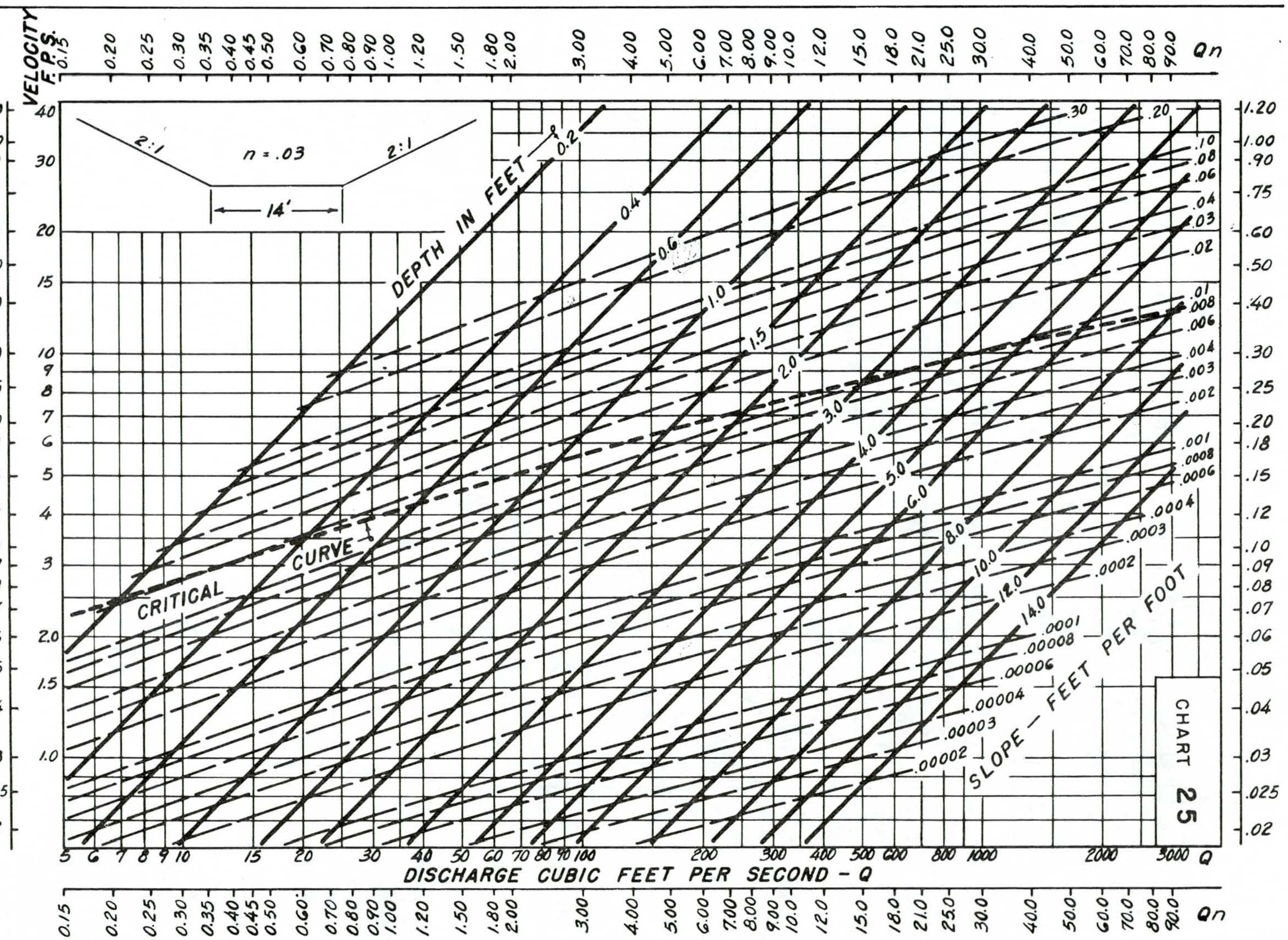
CHANNEL CHART
2:1 b = 10 FT.

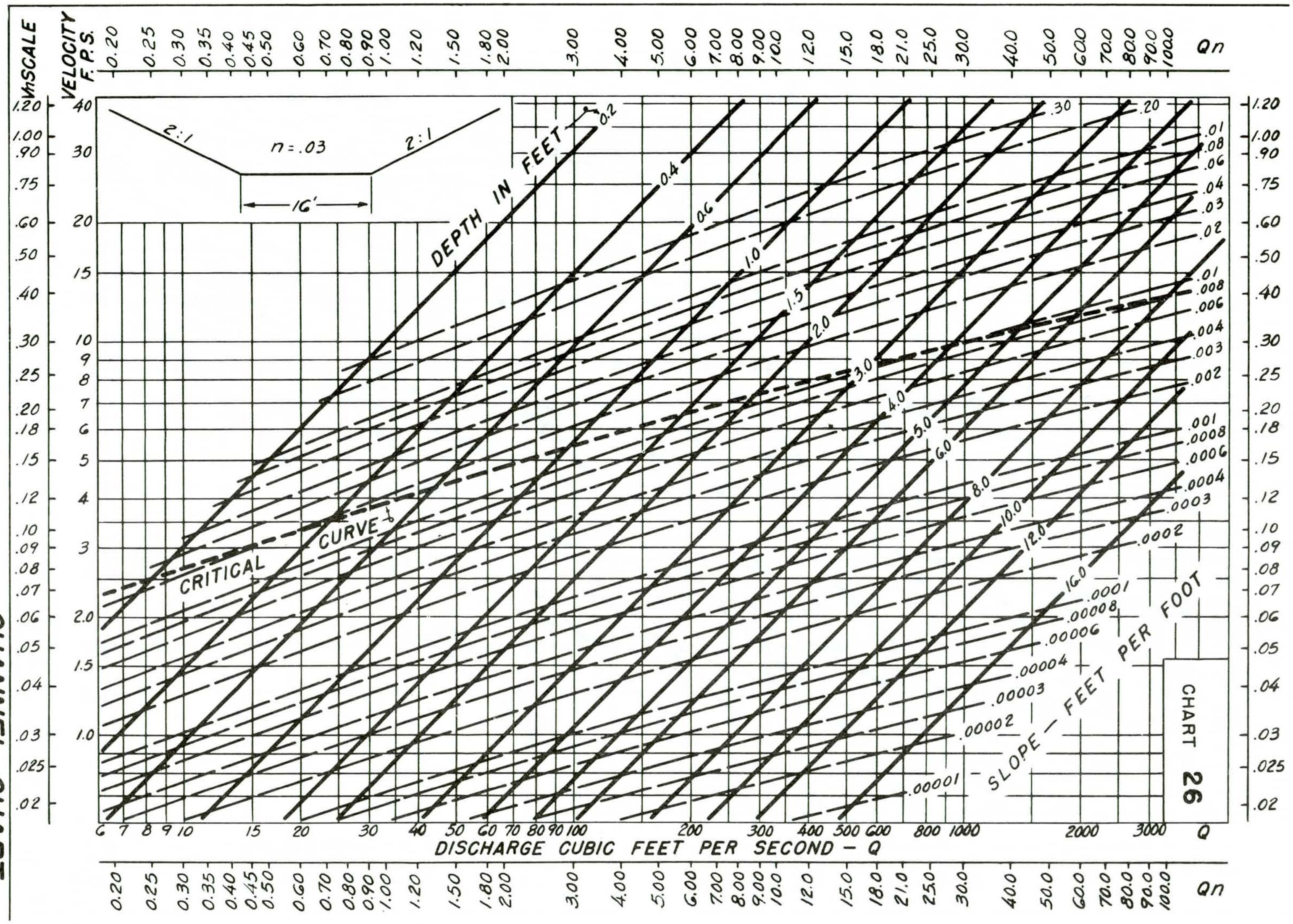




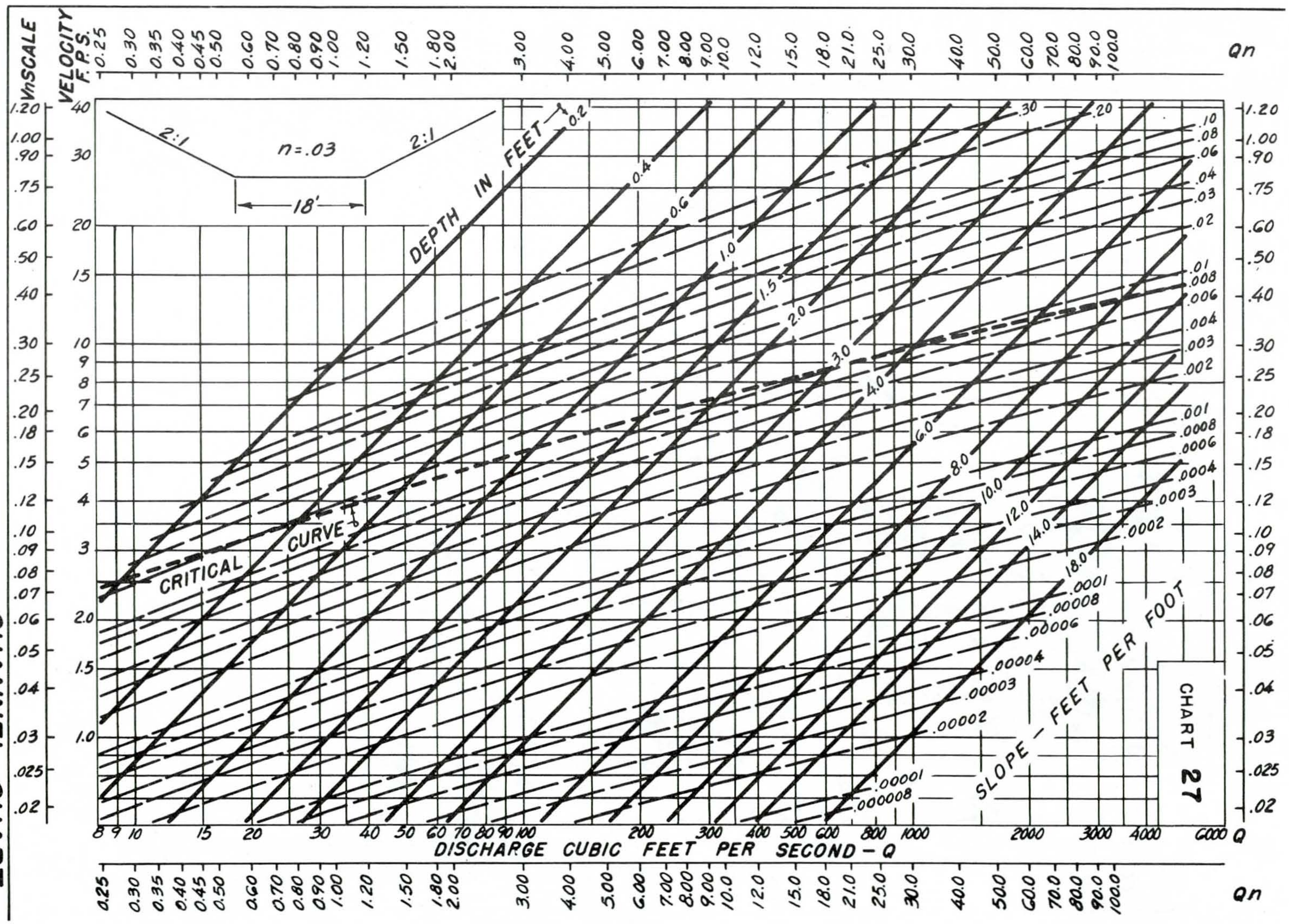
CHANNEL CHART
2:1 b = 12 FT.

CHANNEL CHART
2:1 b = 14 FT.

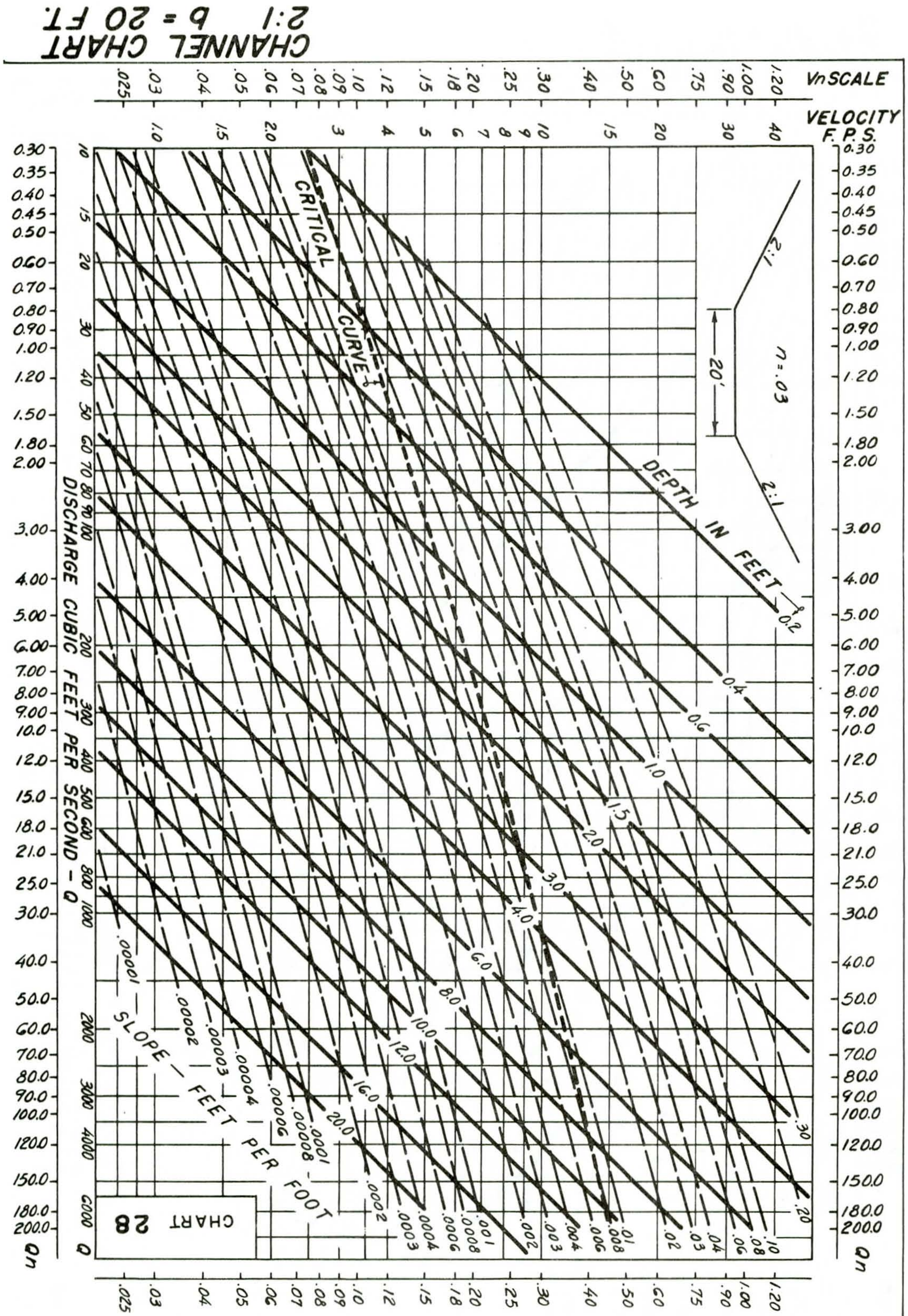




CHANNEL CHART
2:1 b = 16 FT.

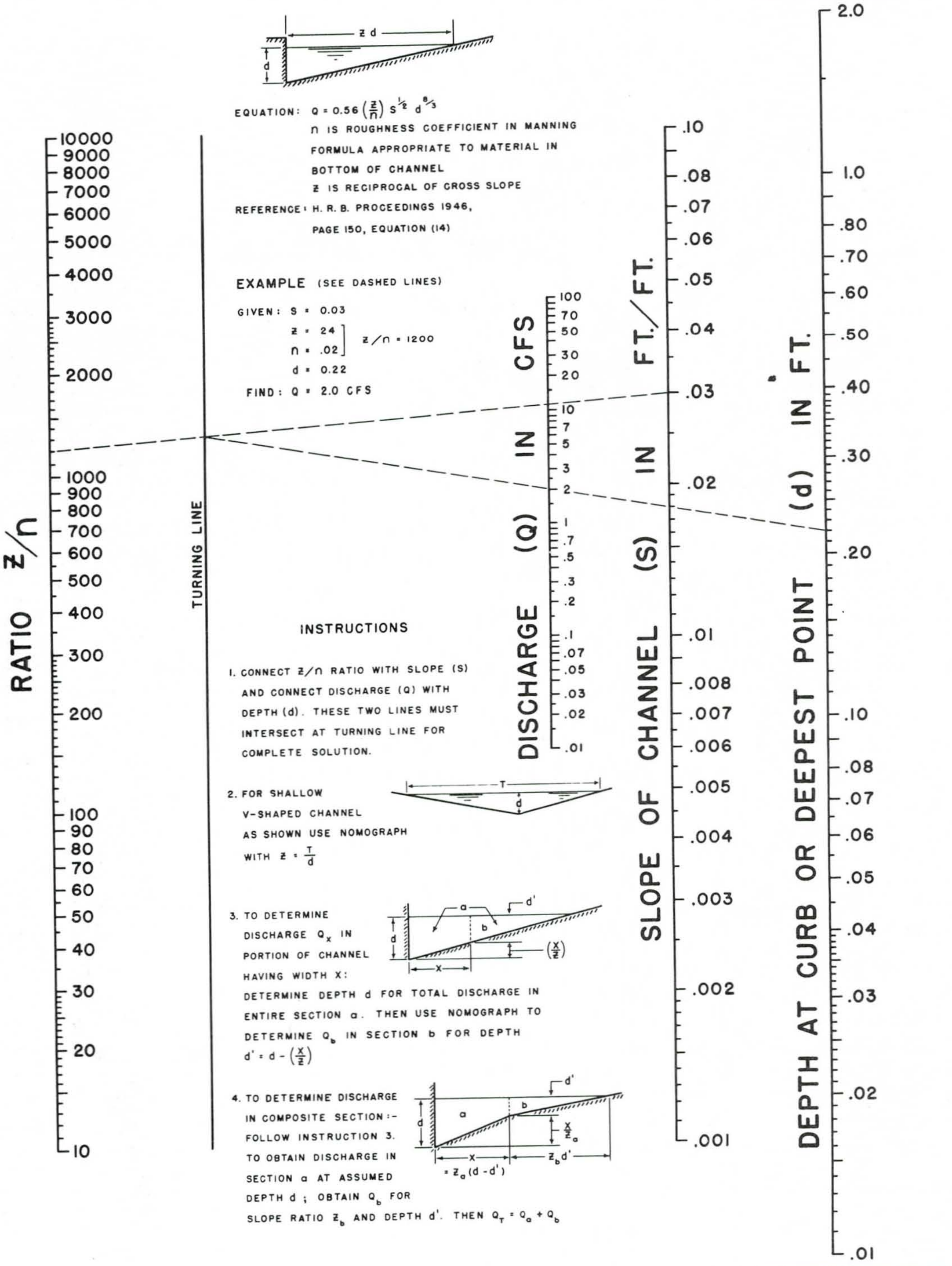


CHANNEL CHART
2:1 b = 18 FT.



CHANNEL CHART
2:1 b = 20 FT.
Vn SCALE
VELOCITY F.P.S.
Qn
DISCHARGE CUBIC FEET PER SECOND – Q
CRITICAL CURVE
DEPTH IN FEET
SLOPE – FEET PER FOOT
n = .03
20'
2:1
CHART 28

CHART 29



NOMOGRAPH FOR FLOW IN TRIANGULAR CHANNELS

Chapter 4.—GRASSED CHANNELS

4.1 Description of charts. Charts 30–34 are designed for use in the direct solution of the Manning equation for various channel sections lined with grass. Charts 30–33 are for trapezoidal cross-section channels, in each case with a 4-foot bottom width, but with side slopes, respectively, of 2:1, 4:1, 6:1, and 8:1. Chart 34 is for a triangular cross-section channel with a side slope of 10:1.

The charts are similar in appearance and use to those or trapezoidal cross sections (charts 15–28, described in chapter 3). However, their construction (see appendix B) is much more difficult because the roughness coefficient n varies with the type and height of grass and with the velocity and depth of flow. The effect of velocity and depth of flow on n may be evaluated by the product of velocity and hydraulic radius, VR. The variation of Manning's n with the retardance and the product VR is shown in figure 5, in which four retardance curves are shown. The retardance varies with the height of the grass and the condition of the stand, as indicated in table 5 (see p. 101). Both of these factors depend upon the type of grass, planting conditions, and maintenance practices.

Each of charts 30–34 has two graphs, the upper graph being for retardance D and the lower graph for retardance C. (Retardances A and B, also shown in figure 5, apply to grasses not used in connection with highways.) For grasses commonly used in roadway drainage channels, such as Bermudagrass, Kentucky bluegrass, orchardgrass, redtop, Italian ryegrass, and buffalograss, the retardance may be selected from table 5.

The charts are plotted with discharge, in cubic feet per second, as the abscissa, and slope, in feet per foot, as the ordinate. Both scales are logarithmic. Superimposed on

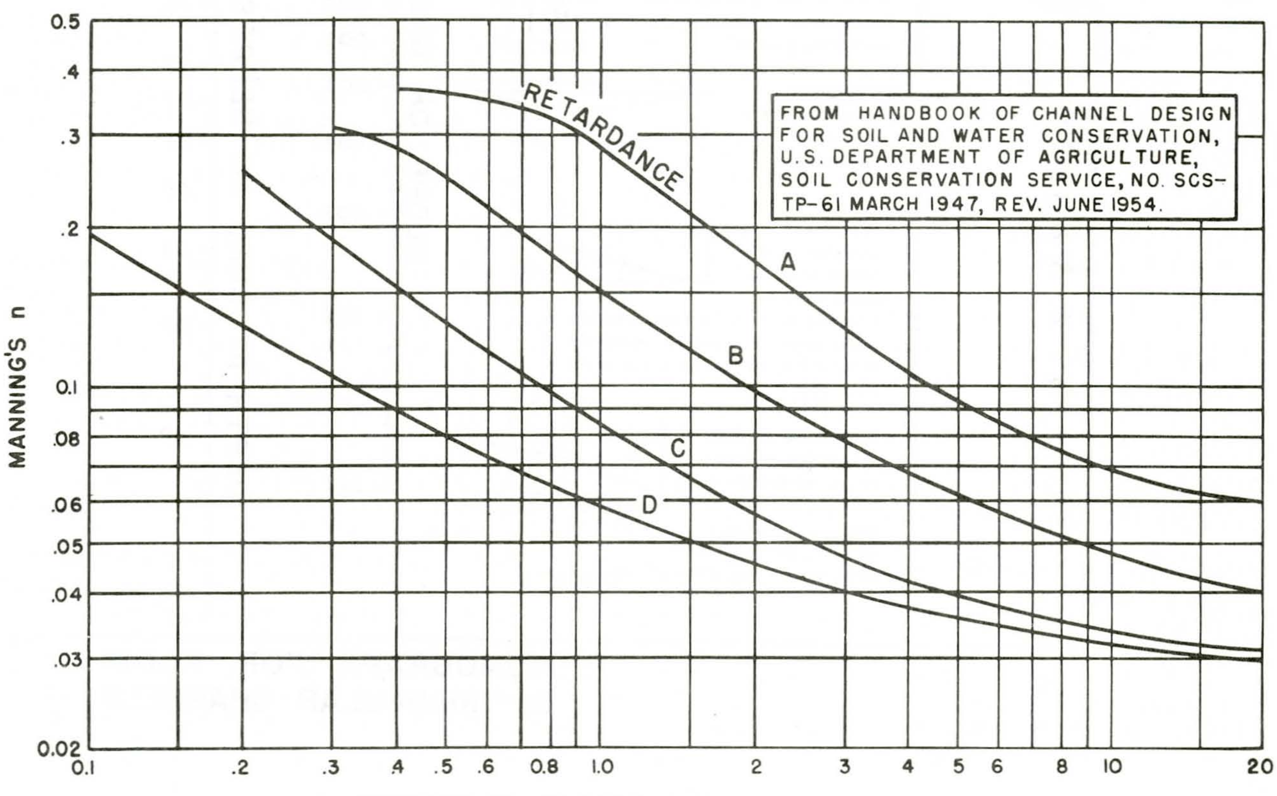


Figure 5.—Degrees of vegetal retardance for which the Manning n has been determined.

the logarithmic grid are lines for velocity, in feet per second, and lines for depth, in feet. A dashed line shows the position of critical flow.

4.2 General instructions for use of charts 30–34. Charts 30–34 provide a solution of the Manning equation for flow in open grassed channels of uniform slope and cross section, provided the flow is not affected by backwater and the channel has a length sufficient to establish uniform flow. The charts provide accuracy sufficient for design of highway drainage channels of fairly uniform cross section and slope. Rounding of the intersection of the side slopes with the bottom of the channel does not appreciably affect the channel capacity.

The design of grassed channels requires two operations: First, finding a section which has the capacity to carry the design discharge on the available slope; and second, checking the velocity developed in the channel to ensure that the grass lining will not be eroded. The need to consider retardance has already been noted (section 4.1). Because the retardance of the channel is largely beyond the control of the designer, he should compute the channel capacity using retardance C; but should compute the velocity for checking with the permissible velocity (see table 3, p. 101) using retardance D. The use of the charts is explained in the following steps:

Select the channel cross section to be used and find the appropriate chart.

Enter the lower graph (for retardance C) on the chart with the design discharge value, on the abscissa, and move vertically to the value of the slope, on the ordinate scale. At this intersection, read the normal velocity and normal depth, and note the position of the critical curve. If the intersection point is below the critical curve, the flow is subcritical; if it is above, the flow is supercritical.

To check the velocity developed against that permissible (table 3), enter the upper graph on the same chart, and repeat the steps described in the preceding paragraph. Then compare the computed velocity with that permissible for the type of grass, the channel slope, and the soil resistance of the channel.

Example 6

Given: A trapezoidal channel, in easily eroded soil, lined with good Bermudagrass sod, with 4:1 side slopes, and a 4-ft. bottom width, on a 2-percent slope ($S=0.02$), discharging 20 c.f.s. *Find:* Depth, velocity, type of flow, and adequacy of grass to prevent erosion.

1. Select chart for 4:1 side slopes, chart 31.

2. Enter the lower graph, for retardance C, with $Q=20$ c.f.s., and move vertically to the line for $S=0.02$ (ordinate scale). At this intersection read $d_n=1$ ft., and normal velocity $V=2.6$ f.p.s.

3. The velocity for checking the adequacy of the grass cover should be obtained from the upper graph, for retardance D. Using the same procedure as in step 2, the developed velocity is found to be 3.1 f.p.s. This is about half of that listed as permissible, 6 f.p.s., in table 3. It is interesting to note that the 1-ft. depth channel indicated in step 2 will carry 30 c.f.s. if the grass is well mowed when the design flood occurs (as read on the upper graph of chart 31).

Example 7

Given: The channel and discharge of example 6. *Find:* The maximum grade on which the 20 c.f.s. could be safely carried.

1. With an increase in slope, the allowable velocity (see table 3) will probably be 5 f.p.s. On the upper graph of chart 31, for short grass the intersection of the 20 c.f.s. line and the 5 f.p.s. line indicates a slope of 6.4 percent and a depth of 0.62 ft.

2. If the grass were allowed to grow to a height of 12 inches, retardance would increase to class C and the depth of flow can be found in the lower graph. Again using 20 c.f.s. and a slope of 6.4 percent, a depth of 0.70 ft. is indicated.

Example 8

Given: A 20-ft. wide median swale with 10:1 side slopes, rounded at the bottom, on a 3-percent slope ($S=0.03$), with a good stand of Bermudagrass, mowed to a 4-in. length, and discharging 3 c.f.s. *Find:* Depth, adequacy of grass protection, and adequacy of the median width.

1. Select the chart for 10:1 slope, chart 34. Table 5 shows a retardance D for 4-in. grass; hence the upper graph of chart 34 is used.

2. At the intersection of $S=0.03$ and $Q=3$ c.f.s., the depth is indicated as 0.54 ft. and the velocity as 1.0 f.p.s. Depth must be measured from the projected intersection of the side slopes, not the rounded bottom.

3. If the grass were allowed to grow taller than 6 inches, the retardance would become C and the lower graph of chart 34 is used. This gives a depth of 0.76 ft., which is less than the available depth of 1 ft. for the 20-ft. median with 10:1 side slopes. The grass will stand much higher velocities than 1 f.p.s., according to table 3. Thus the swale dimensions and the grass cover are adequate for the flow.

Example 9

The problem presented and solved in example 8 can also be solved by using the triangular cross-section channel nomograph, chart 29, of chapter 3. This method would be needed if the side slopes were less than 10:1, but ought not to be used for steeper side slopes.

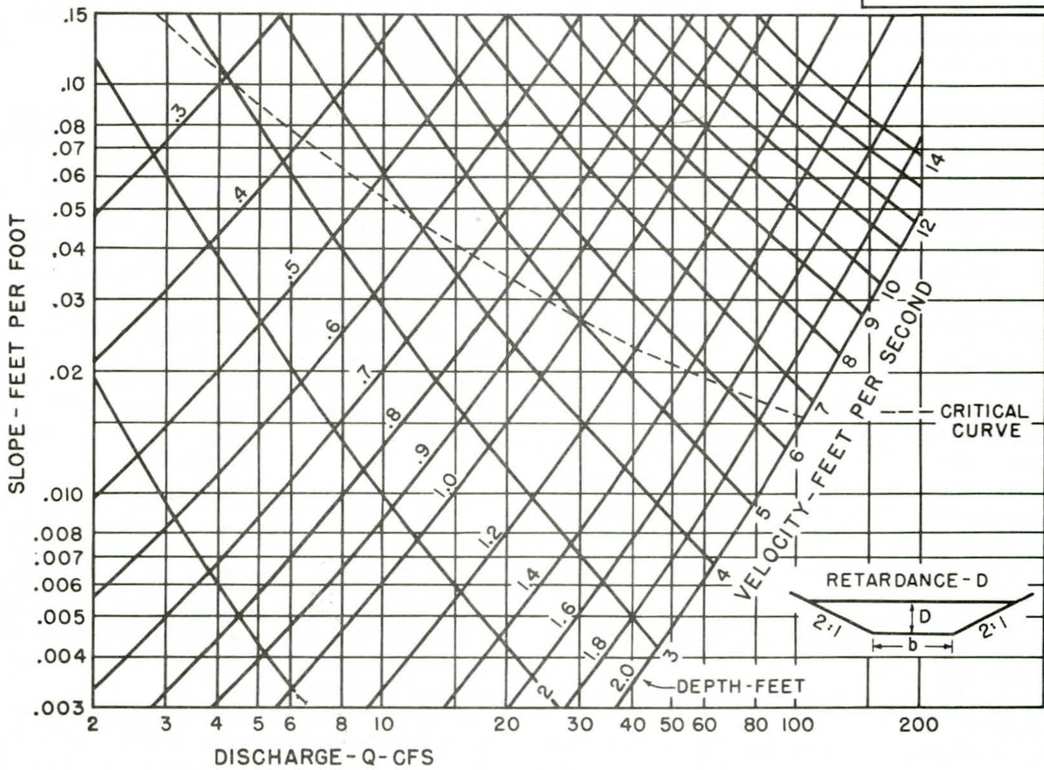
1. Find n in table 1. If the depth is assumed to be less than 0.7 ft. and the velocity less than 2 f.p.s., n for Bermudagrass is 0.09.

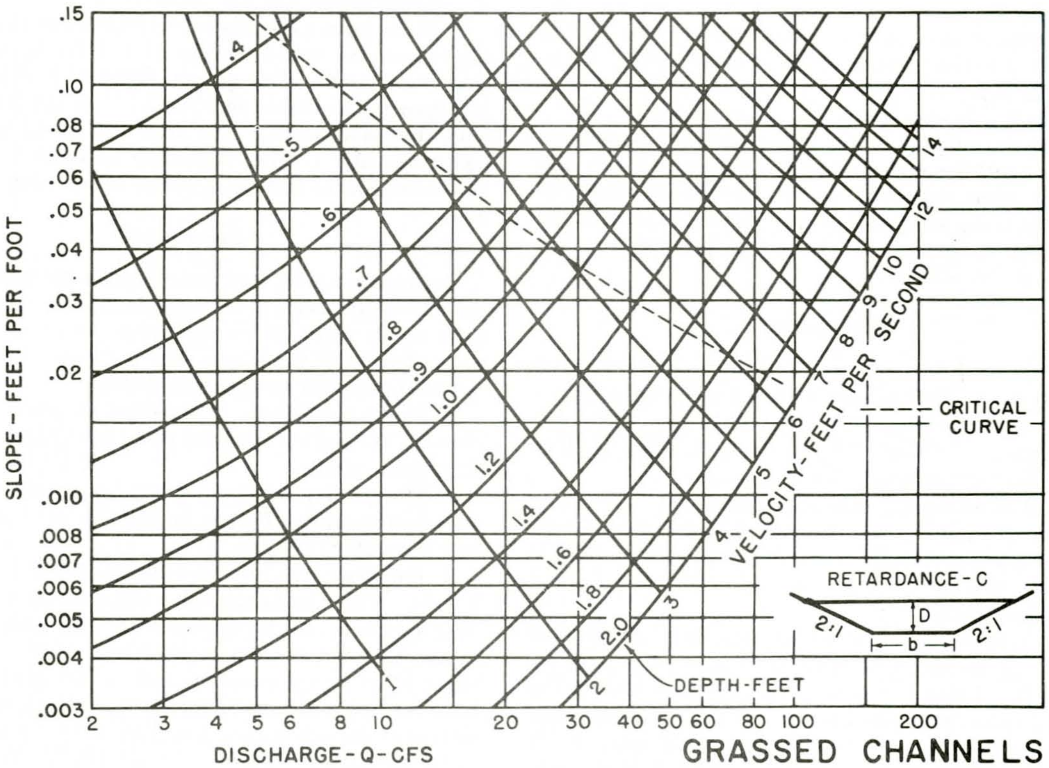
2. The median being considered is, in effect, a shallow V-shaped channel. For use in chart 29, $Z=T/d=20/1=20$; and $Z/n=20/0.09=222$.

3. For $Z/n=222$, on chart 29, the depth is found to be 0.48 ft. This checks the value obtained by using chart 34 (in example 8), to the nearest tenth of a foot.

The rounded bottom of the swale would have only a slight effect on the capacity, and can be ignored. Depth, however, must always be measured to the projected intersection of the side slopes, and not just to the deepest point of the rounded bottom.

CHART 30

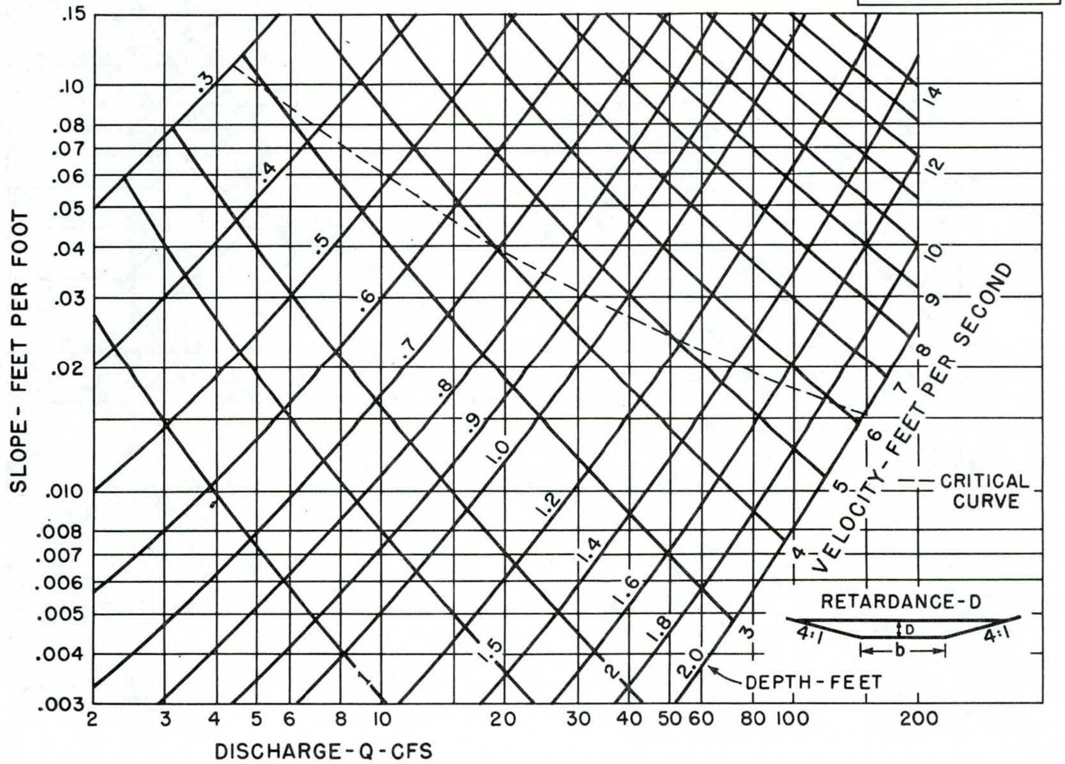


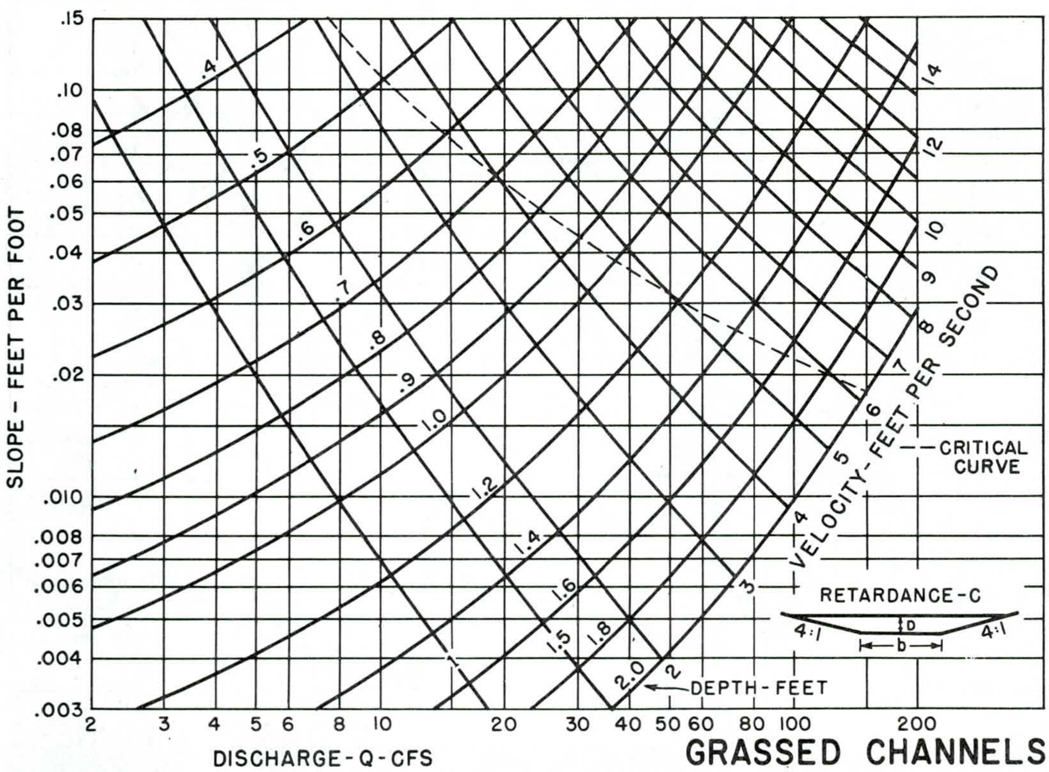


GRASSED CHANNELS

2:1 b = 4 ft.

CHART 31

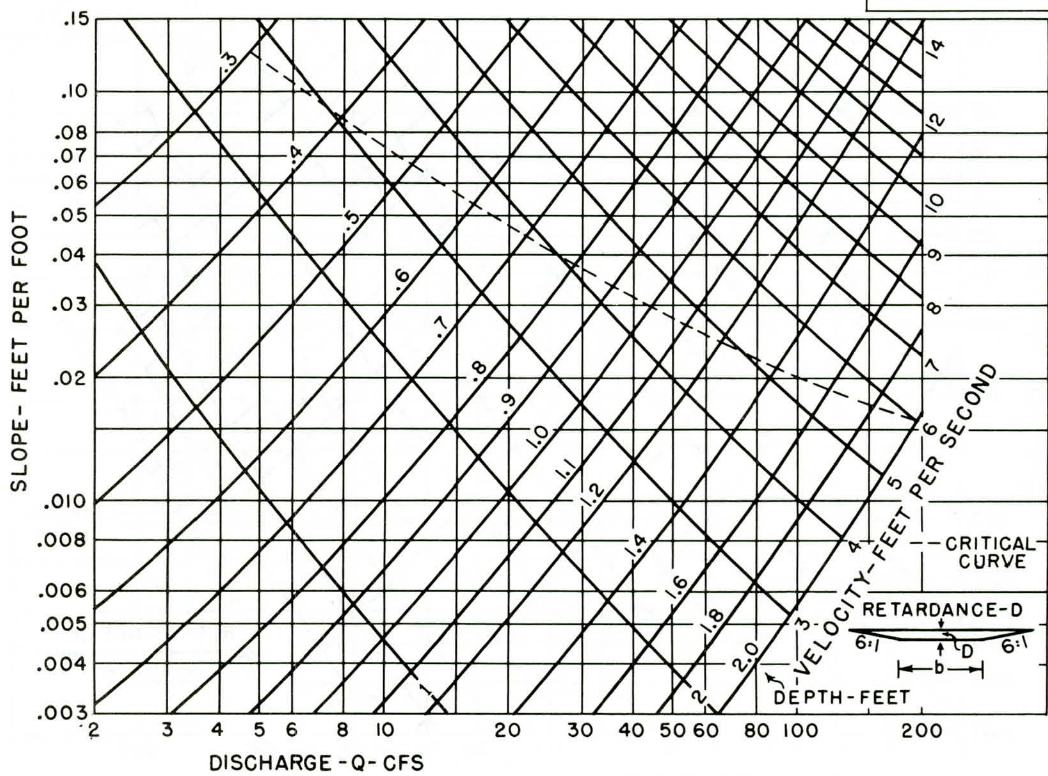


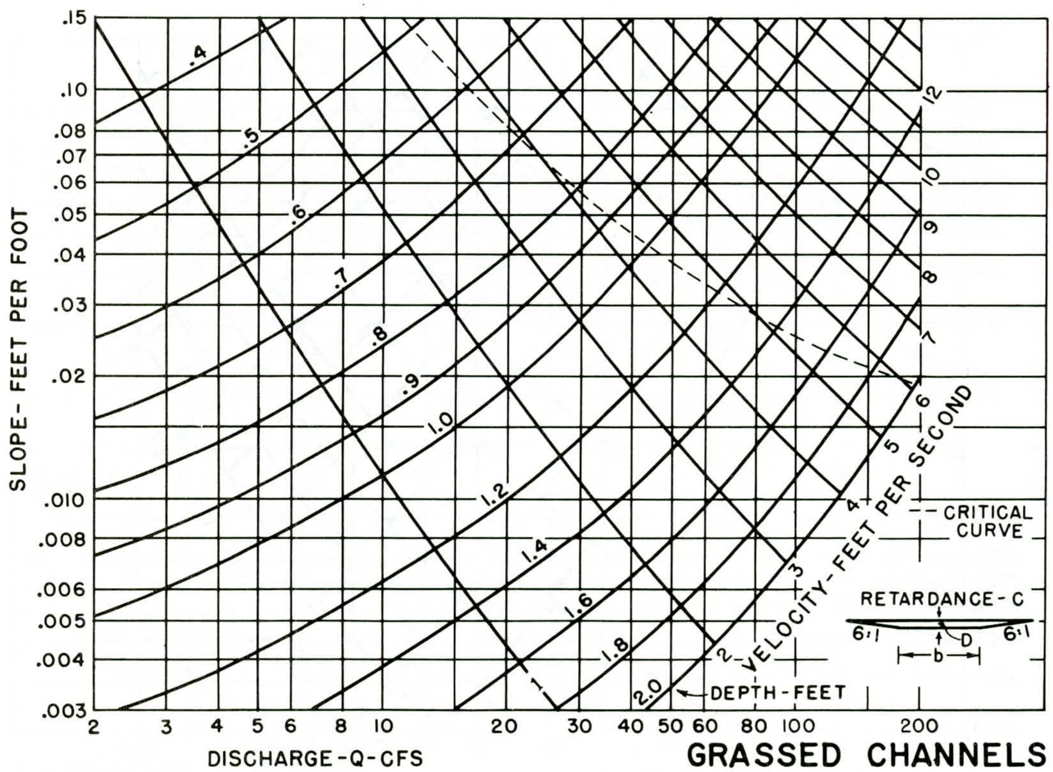


GRASSED CHANNELS

4:1 b = 4 ft.

CHART 32

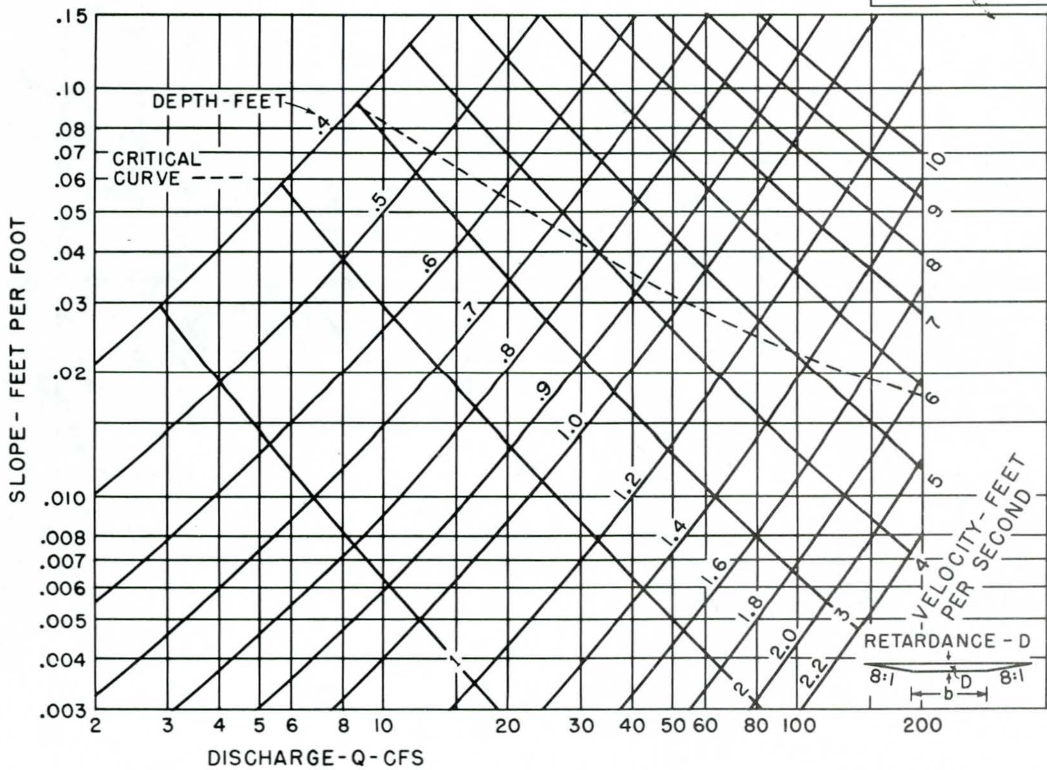


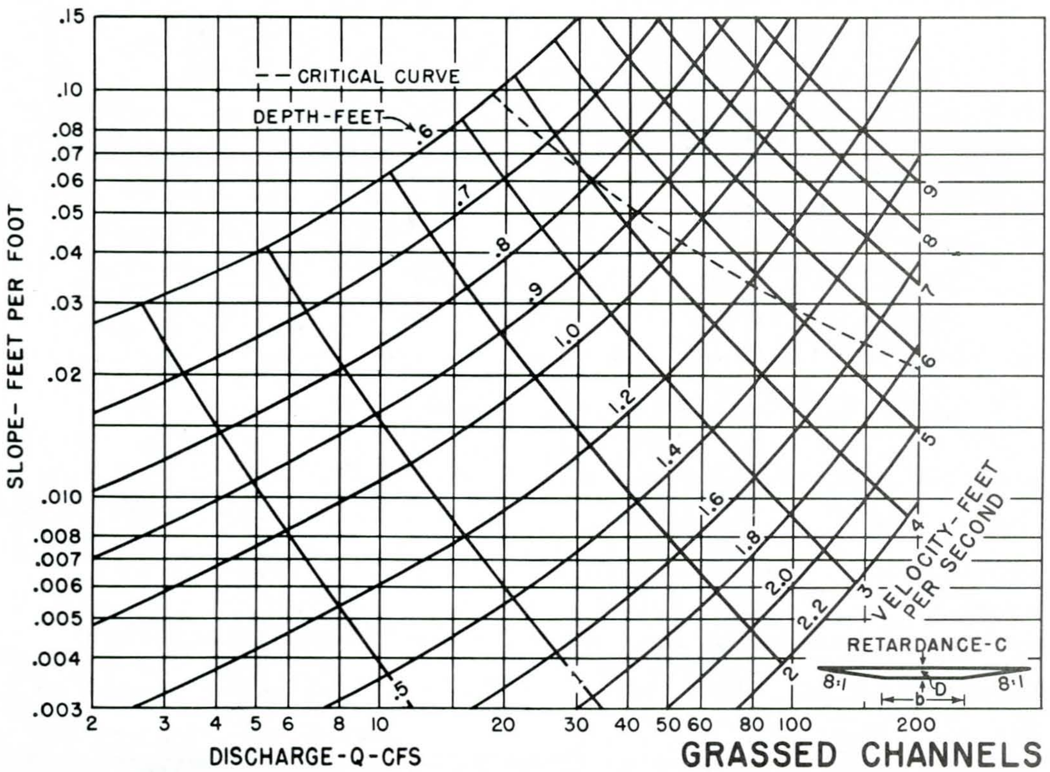


GRASSED CHANNELS

6:1 b = 4 ft.

CHART 33

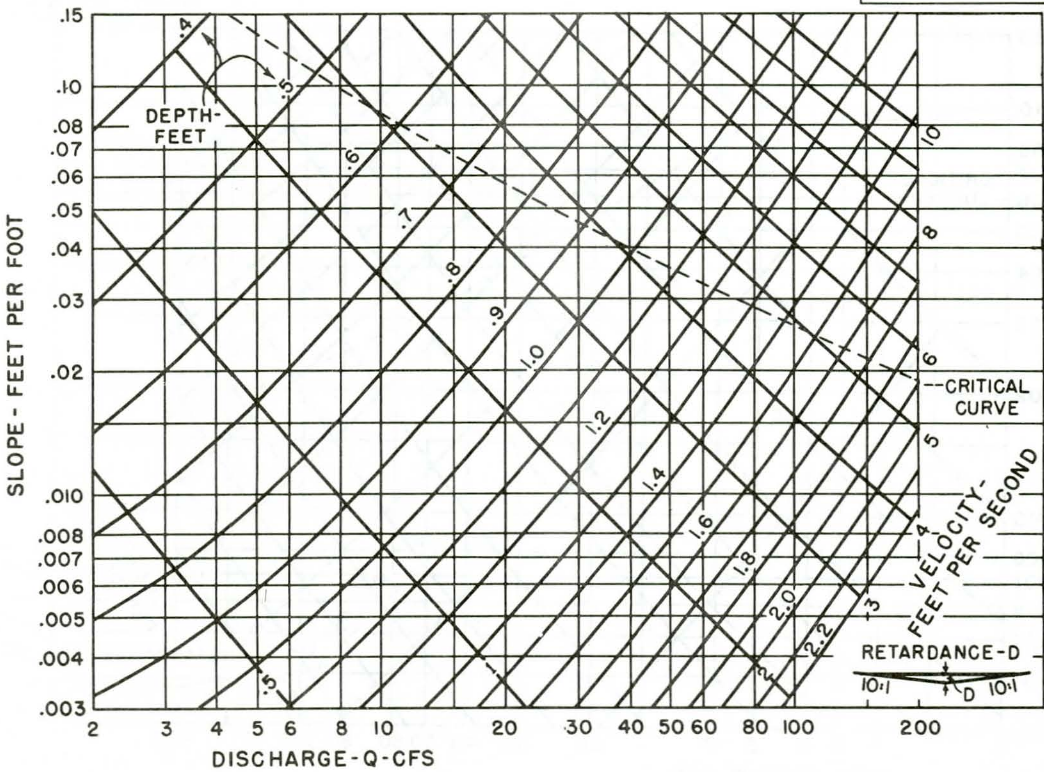


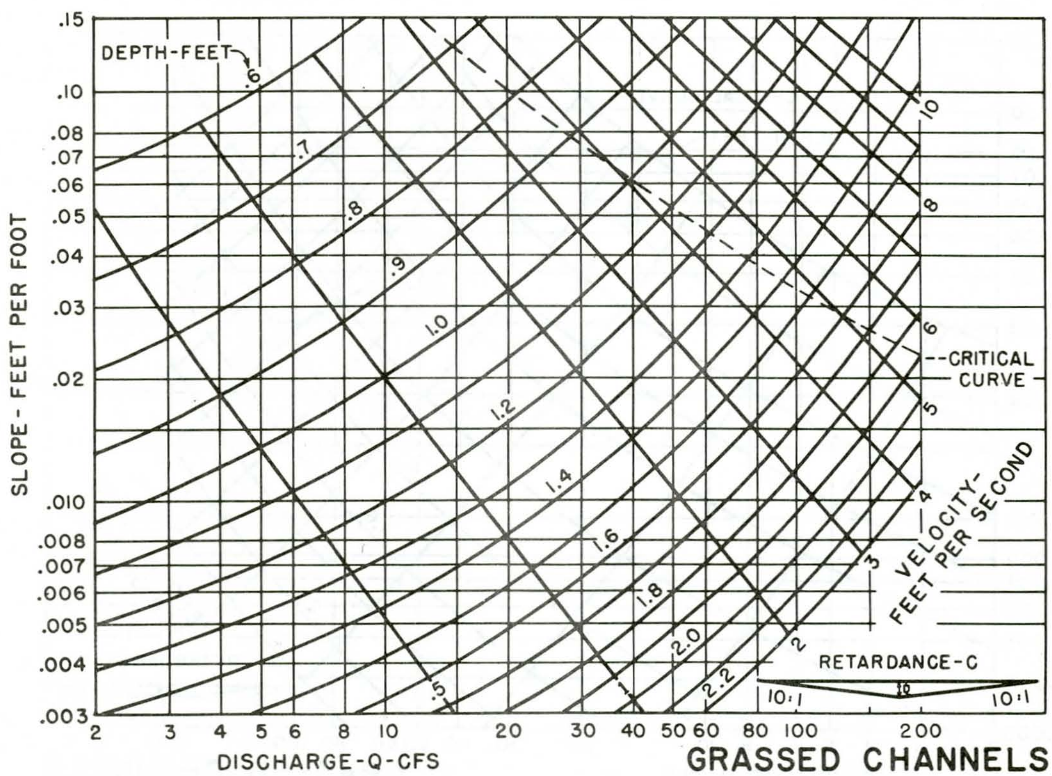


GRASSED CHANNELS

8:1 b = 4 ft.

CHART 34





GRASSED CHANNELS
10:1

Chapter 5.—CIRCULAR-PIPE CHANNELS

5.1 Description of charts. Charts 35–60 are designed for use in the solution of the Manning equation for circular-pipe channels which have sufficient length, on constant slope, to establish uniform flow at normal depth without backwater or pressure head. It is important to recognize that they are not suitable for use in connection with most types of culvert flow, since culvert flow is seldom uniform.

The charts are of two types. Charts 35–51, whose use is described in section 5.2, are similar to the open-channel charts of chapter 3. Separate charts are provided for pipe diameters of 12–36 inches, by 3-inch increments; for diameters of 42–72 inches, by 6-inch increments; and for diameters of 84 and 96 inches. The charts are prepared for an n of 0.015, with auxiliary scales for $n=0.012$ and 0.024. Instructions are given for using the charts with any other value of n, in section 5.2–2. The charts have an abscissa scale of discharge, in cubic feet per second, and an ordinate scale of velocity, in feet per second. Both scales are logarithmic. Superimposed on the logarithmic grid are steeply inclined lines representing depth (in feet), and slightly inclined lines representing channel slope (in feet per foot). A heavy dashed line on each chart shows the position of critical flow.

The second set of charts for circular-pipe channels, Nos. 52–60, whose use is described in section 5.3, differ from charts 35–51 in that they require the use of several charts for solving the Manning equation. The charts contain curves for standard sizes of pipe up to 15 feet in diameter, for values of $n=0.011$, 0.012, and 0.025. The relations of friction slope, discharge, velocity, and pipe diameter for pipes with $n=0.025$ are given on chart 52; similar relations for pipes with $n=0.011$ and 0.012 are given on charts 53 and 54. Ratios for computation of part-full pipe flow are given on chart 55. Chart 56 shows critical depth and chart 57 shows specific head at critical depth; both are independent of the n value of the pipe. Chart 58 shows the critical slope for pipes with $n=0.025$, and charts 59 and 60 show critical slope for pipes with n values of 0.011 and 0.012.

5.2 Instructions for use of charts 35–51, for pipes 1–8 feet in diameter. Charts 35–51 cover pipe sizes from 12 to 96 inches in diameter. It will be noted that each slope line has a hook at its right terminus. If d_n is greater than 0.82 diameter, two values of d_n will be shown by the slope line hook for a particular value of Q. In these cases, flow will occur at the lesser of the alternate depths. Interpolated slope lines follow the same pattern as those drawn on the charts.

The maximum rate of uniform discharge in a circular pipe on a given slope, when not flowing under pressure, will occur with a depth of 0.94 diameter. This discharge can be determined by reading the highest Q, on the appropriate n scale, which can be read on the given slope line.

5.2–1 Use of charts with basic chart-design value of n. For a given discharge, slope, and pipe size, the depth and velocity of uniform flow may be read directly from the chart for that size pipe. The initial step is to locate the intersection of a vertical line through the discharge (on the appropriate n scale) and the appropriate slope line. At this intersection, the depth of flow is read or interpolated from the depth lines; and the mean velocity is read opposite the intersection on the velocity scale for the n value of the pipe (see examples 10 and 11). The procedure is reversed to determine the discharge at a given depth of flow. If the discharge line passes to the right of the appropriate slope line, the pipe will flow full (in which case, see sec. 5.2–3).

Critical depth and critical velocity are independent of the value of n. They are read at the point where a vertical line through Q, on the scale $n=0.015$, intersects the critical curve. Critical slope for $n=0.015$ is also read or interpolated from the slope line at the same intersection. For n values of 0.012 and 0.024, critical slope is determined by first finding critical depth, using Q on the scale $n=0.015$. Critical slope is then read or interpolated from the slope lines at the intersection of critical depth and the vertical line through Q on the appropriate n scale (see example 11). Critical depths falling between the last two normal depth lines have little significance, since wave action may intermittently fill the pipe.

Example 10

Given: A long 30-inch concrete pipe, with $n=0.015$, on a 0.5-percent slope ($S=0.005$), discharging 25 c.f.s. *Find:* Depth, velocity, and type of flow.

1. Select the chart for a 30-inch pipe, chart 41.
2. From 25 on the Q scale for $n=0.015$, move vertically to intersect the slope line $S=0.005$; at the intersection, from the depth lines read $d_n=2.05$ ft.
3. Move horizontally from the intersection and read the normal velocity, $V_n=5.8$ f.p.s., on the ordinate scale.
4. The intersection lies below the critical curve, and the flow is therefore subcritical. At the intersection of the $Q=25$ c.f.s. (on the scale $n=0.015$) line with the critical curve, the chart shows critical depth $d_c=1.7$ ft. and critical velocity $V_c=6.9$ f.p.s.

Example 11

Given: A long 60-inch corrugated metal pipe with $n=0.024$, on a 2-percent slope ($S=0.02$), discharging 100 c.f.s. *Find:* Depth, velocity, and type of flow.

1. Select the chart for a 60-inch pipe, chart 47.

2. From 100 on the Q scale for $n=0.024$, move vertically to intersect the slope line $S=0.02$, and read $d_n=2.5$ ft.

3. Move horizontally from the intersection and, on the V scale for $n=0.024$, read the normal velocity $V_n=10.5$ f.p.s.

4. Critical depth and critical velocity are independent of the value of n and are read using the n scale (0.015) for which the charts were basically constructed. At the intersection of $Q=100$ c.f.s. (on the $n=0.015$ scale) and the critical curve, the chart shows $d_c=2.8$ ft. and $V_c=8.5$ f.p.s. The normal depth, 2.5 ft., is less than the critical depth, 2.8 ft., and the normal velocity, 10.5 f.p.s., is higher than the critical velocity, 8.5 f.p.s.; thus the flow is supercritical.

5. To find the critical slope, follow the critical depth line, 2.8 ft. (found in step 4), back to its intersection with a vertical line through $Q=100$ c.f.s. on the scale $n=0.024$, and read $S_c=0.015$. The pipe slope, 0.02, is greater than the critical slope, 0.015, which is another indication that the flow is in the supercritical range.

5.2–2 Use of charts with other than basic chart-design values of *n*. For pipes with n values other than 0.015, 0.012, and 0.024, use the scale $n=0.015$ and an adjusted Q obtained by multiplying the design Q by the ratio of the pipe n to the chart value $n=0.015$; that is, $Q_{adj.}=Q\times(n/0.015)$. Read the depth directly at the intersection of the pipe slope line and a vertical line through the adjusted Q. The velocity is read opposite the intersection on the scale $n=0.015$, but this value must be divided by the ratio $n/0.015$ to obtain the pipe velocity (see example 12). In reversing the procedure, to determine the discharge for a given depth and slope, read Q on the scale $n=0.015$ and divide by the ratio $n/0.015$ (see example 12).

Critical depth, velocity, and slope are determined as explained in step 4 of example 12.

Example 12

Given: A long 72-in. field-bolted corrugated metal pipe, with $n=0.030$, on a 0.3-percent slope ($S=0.003$), flowing at a depth of 3.0 ft. *Find:* Discharge, velocity, and type of flow.

1. Select the chart for a 72-in. pipe, chart 49.

2. Locate the intersection of the lines for $d_n=3.0$ ft. and $S=0.003$, and read $Q_{adj.}=100$ c.f.s. and $V_{adj.}=7.0$ f.p.s. on the scales for $n=0.015$.

3. Compute the ratio $n/0.015=0.030/0.015=2.0$; and divide the values of Q and V found in step 2 by this ratio: $Q=100/2.0=50$ c.f.s., and $V=7.0/2.0=3.5$ f.p.s.

4. Critical depth and critical velocity may be read directly on chart 49 by finding the intersection of the critical curve with a vertical line through $Q=50$ c.f.s. (determined in step 3) on the $n=0.015$ scale. These values are $d_c=1.9$ ft. and $V_c=6.5$ f.p.s. The normal depth, 3.0 ft., is greater than d_c, 1.9 ft., and the normal velocity, 3.5 f.p.s., is less than V_c, 6.5 f.p.s.; the flow is therefore in the subcritical range.

5. To find the critical slope, follow the critical depth line, 1.9 ft., to its intersection with a vertical line through $Q_{adj.}=100$ c.f.s. on the $n=0.015$ scale, and read $S_c=0.015$. The pipe slope, 0.003, is less than the critical slope. This is another indication that flow is in the subcritical range.

5.2–3 Pipes flowing full. When, on charts 35–51, a vertical line through the discharge passes to the right of the terminus of the pipe slope line, the pipe will flow full and under pressure. The slope of the pressure and energy lines for full flow can be determined from the charts. These lines are both parallel to the friction slope S_f when the pipe flows full. The friction slope is the rate at which energy is lost by resistance to flow and it will be greater than the pipe slope.

To find S_f, enter the appropriate chart with Q, or $Q_{adj.}$ for values of n other than 0.012, 0.015, and 0.024, and move vertically to intersect the depth line which is equal to the pipe diameter. At the intersection, read or interpolate the friction slope on or between the short right-angle marks indicating slope (see example 13).

Example 13

Given: A long 30-in. corrugated metal pipe, with $n=0.024$, on a 0.8-percent slope ($S=0.008$), discharging 25 c.f.s. *Find:* Friction slope S_f.

1. Select the chart for a 30-in. pipe, chart 41.

2. From 25 on the Q scale for $n=0.024$, move vertically: the objective is to intersect slope line $S=0.008$, but the Q line passes to the right of the end of the 0.008 slope line; therefore, the pipe will flow full.

3. Having verified full flow, proceed vertically on $Q=25$ to intersect the 2.5-ft. depth line, which equals the 30-in. pipe diameter; and read the friction slope $S_f=0.012$.

5.3 Instructions for use of charts 52–60, for pipes 1–15 feet in diameter. Charts 52–60 are used to solve the Manning equation for uniform flow in part-full circular pipes up to 15 feet in diameter and with n values of 0.011, 0.012, and 0.025. Charts 52–55 are for normal flow and require, first, finding the friction slope for the given discharge in a pipe flowing full. For this purpose, use chart 52 for $n=0.025$, and chart 53 or 54, depending on pipe size, for $n=0.011$ or 0.012. Then the ratio graphs of chart 55 are used to find discharge Q, depth d, velocity V, and friction slope S_f.

Chart 56 is used to determine critical depth d_c, and chart 57 to determine specific head H_c at critical depth. To find critical slope S_f, chart 58 is used for $n=0.025$, and chart 59 or 60, depending on pipe size, for $n=0.011$ or 0.012.

It will be noted that charts 52 and 58 for corrugated metal pipe are based on $n=0.025$. For 6- by 2-inch corrugations, current laboratory tests indicate that the value of n should be higher. When the final results of these tests are published, the user may wish to add a slope scale for the new value of n to charts 52 and 58. Such scales could be placed as are the $n=0.012$ scales on charts 53 and 59.

5.3–1 Use of charts to find discharge. The following steps are used to find discharge, when depth of flow and slope of pipe are known (see example 14).

First find full-flow discharge Q_{FULL} corresponding to the slope of the pipe, using chart 52, 53, or 54, according to the n value and the size of pipe.

Next compute d/D, the ratio of depth of flow to the diameter of the pipe, and on chart 55 read the corresponding Q/Q_{FULL} on the relative discharge curve in the upper graph.

Finally, compute the discharge at the given depth by multiplying the full-flow discharge (from the first step) by the ratio Q/Q_{FULL} (from the second step).

5.3–2 Use of charts to find depth of uniform flow. The following steps are used to find depth of uniform flow, when discharge and slope are known (see example 15).

First find Q_{FULL} corresponding to the slope of the pipe, using chart 52, 53, or 54, according to the n value and the size of pipe.

Next compute the ratio Q/Q_{FULL}, and on chart 55 read the corresponding d/D on the relative discharge curve in the upper graph.

Finally, compute the depth of flow by multiplying the pipe diameter by the ratio d/D (from the second step). D and d must be in the same units.

5.3–3 Use of charts to find velocity of flow. The following steps are used to find velocity of flow, when discharge and slope are known (see example 15).

First find V_{FULL} corresponding to the given discharge rate, using chart 52, 53, or 54, according to the n value and the size of pipe.

If the depth of flow is unknown, it is determined as indicated in section 5.3–2.

Next compute the ratio d/D, and on chart 55 read the corresponding V/V_{FULL} on the relative velocity curve in the upper graph.

Finally, compute the mean velocity V of part-full flow by multiplying V_{FULL} (from the first step) by the ratio V/V_{FULL} (from the third step).

5.3–4 Use of charts to find slope required to maintain flow. The following steps are used to find slope required to maintain flow, when discharge and depth are known (see example 16).

First find $S_{f\ FULL}$ corresponding to the discharge, using chart 52, 53, or 54, according to the n value and the size of pipe.

Next compute the ratio d/D, and on chart 55 read the relative friction slope $S_f/S_{f\ FULL}$ on the lower graph.

Finally, compute the friction slope S_f by multiplying $S_{f\ FULL}$ (from the first step) by the ratio $S_f/S_{f\ FULL}$ (from the second step).

5.3–5 Use of charts to find critical flow. The following steps are used to find critical flow (see example 17), for a given discharge.

Critical depth d_c is read on chart 56 at the intersection of Q and the pipe size.

Minimum specific head H_c is read on chart 57 at the intersection of Q and the pipe size.

Critical slope S_c is read on chart 58, 59, or 60, selected according to the n value and pipe size, at the intersection of Q and the pipe size.

Example 14

Given: A long 48-in. diameter concrete pipe, with $n=0.011$, on a 0.5-percent slope ($S=0.005$), flowing at a depth of 3.0 ft. *Find:* Discharge.

1. On chart 54, using the $n=0.011$ scales, find the intersection of the lines for a 48-in. pipe and $S=0.005$. From this point move vertically down to read $Q_{FULL}=120$ c.f.s.
2. The ratio of $d/D=3.0/4.0=0.75$. In the upper graph of chart 55, move across from this value to the relative discharge curve, and thence up to the top scale to find the relative discharge, 0.91.
3. Then $Q=120$ (from step 1)$\times 0.91=109$ c.f.s.

Example 15

Given: A long 10-ft. diameter concrete pipe, with $n=0.012$, on a 0.06-percent slope ($S=0.0006$), discharging 315 c.f.s. *Find:* Depth and velocity.

1. On chart 54, using the $n=0.012$ scale, find the intersection of the lines for a 10-ft. pipe and $S=0.0006$, and read $Q_{FULL}=440$ c.f.s.
2. The ratio $Q/Q_{FULL}=315/440=0.72$. In the upper graph of chart 55, from the intersection of this value and the relative discharge curve, read the d/D ratio$=0.63$.
3. Then $d_n=0.63\times 10=6.3$ ft.
4. On chart 54, at the intersection for $Q=315$ c.f.s. and $D=10.0$ ft., read $V_{FULL}=4.0$ f.p.s.
5. From the intersection of the d/D ratio of 0.63 and the relative velocity curve, on the upper graph of chart 55, read $V/V_{FULL}=1.50$.
6. Then $V_n=1.50\times 4.0$ (from step 4)$=6.0$ f.p.s.

Example 16

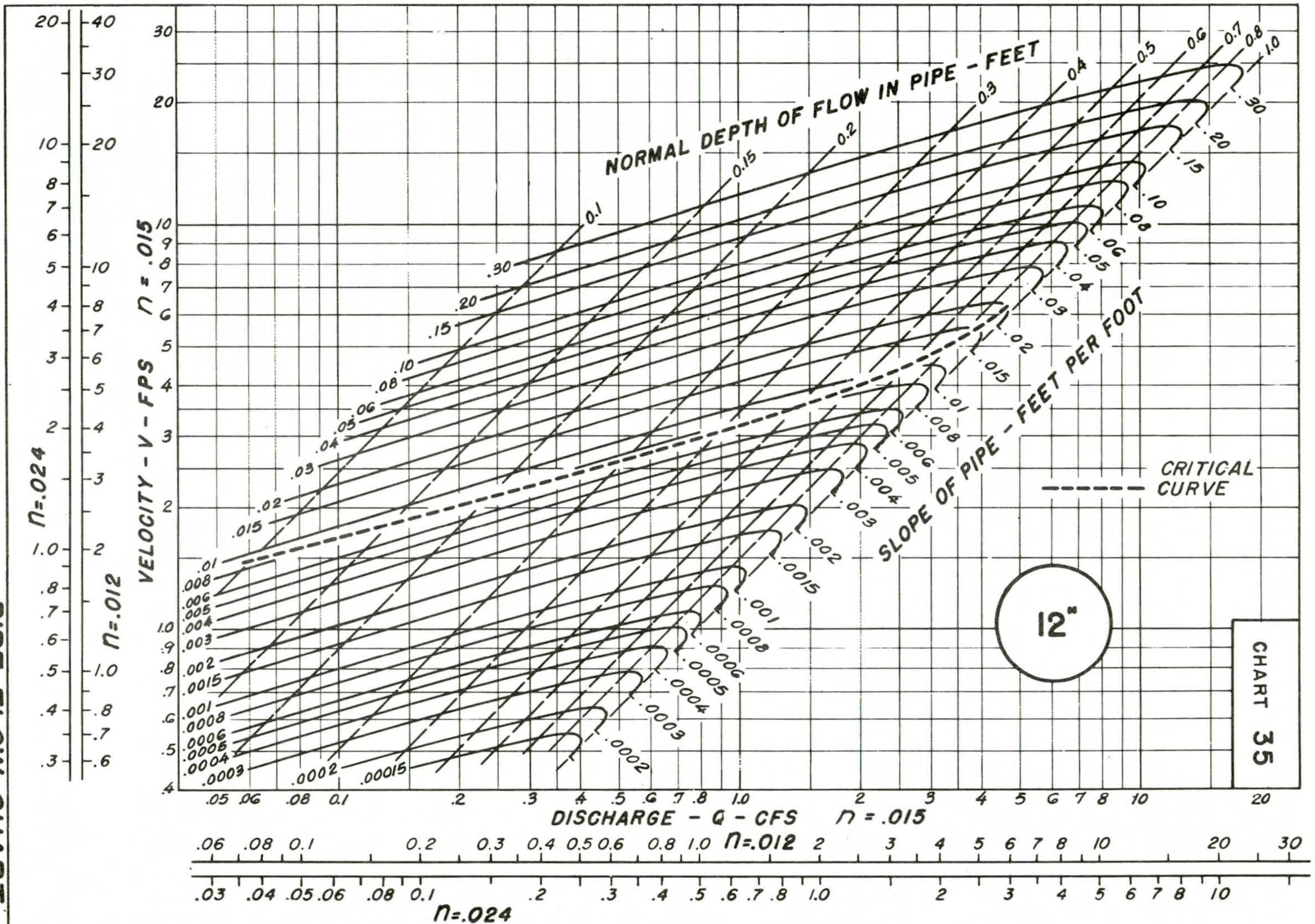
Given: A long 10-ft. corrugated metal pipe, with $n=0.025$, discharging 600 c.f.s. at a depth of flow of 7.5 ft. *Find:* Slope S_f required to maintain the flow, and the critical slope S_c for the given conditions.

1. On chart 52, at the intersection of $Q=600$ c.f.s. and the pipe diameter 10 ft., read $S_{f\ FULL}=0.0048$.
2. The d/D ratio$=7.5/10.0=0.75$, and on the lower graph of chart 55, the corresponding ratio $S_f/S_{f\ FULL}=1.2$.
3. Then $S_f=1.2\times 0.0048$ (from step 1)$=0.0058$.
4. On the lower graph of chart 58, for $Q=600$ c.f.s. and $D=10$, $S_c=0.012$.

Example 17

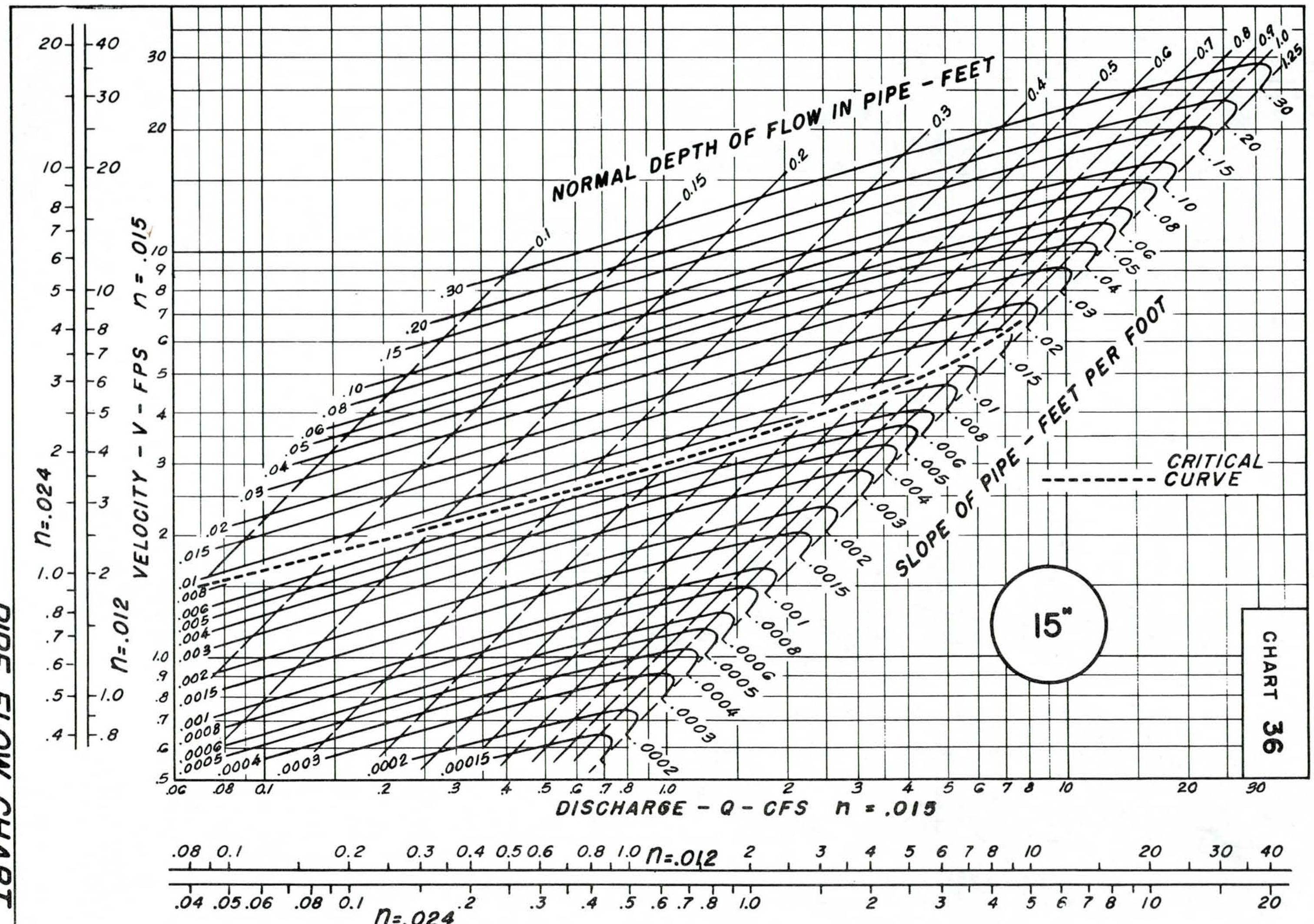
Given: A long 10-ft. concrete pipe, with $n=0.012$, discharging 600 c.f.s. *Find:* Critical depth d_c, critical slope S_c, and specific head H_c at d_c.

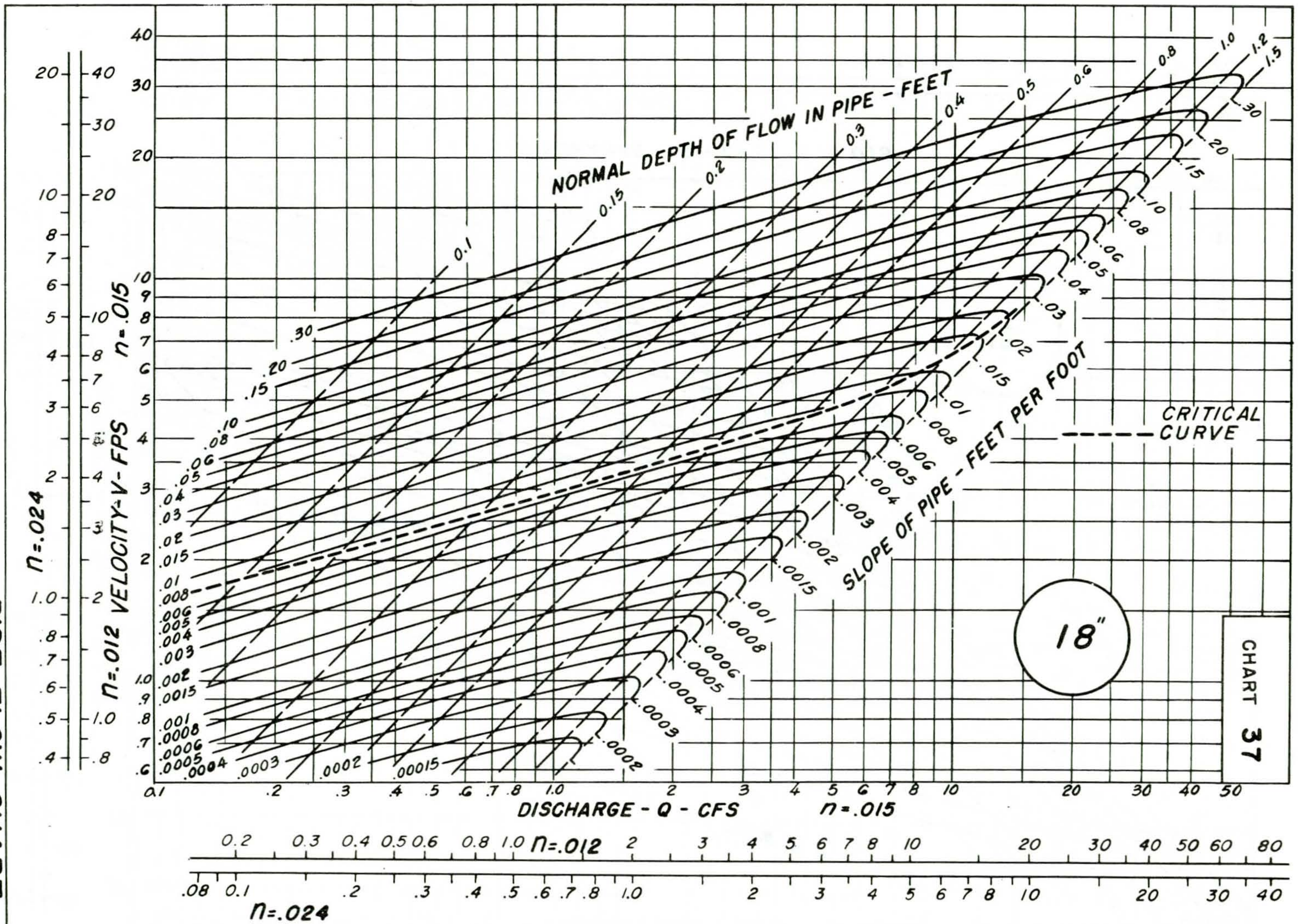
1. On the lower graph of chart 56, for $Q=600$ c.f.s. and $D=10$ ft., read $d_c=5.9$ ft. (Note that in this case, D is interpolated between the next larger and next smaller pipe sizes.)
2. On the upper graph of chart 60, for $Q=600$ c.f.s. and $D=10$ ft., and using the right margin scale, $S_c=0.0026$.
3. On the lower graph of chart 57, for $Q=600$ c.f.s. and $D=10$ ft., read $H_c=8.4$ ft. (See note at end of step 1.)



PIPE FLOW CHART
12-INCH DIAMETER

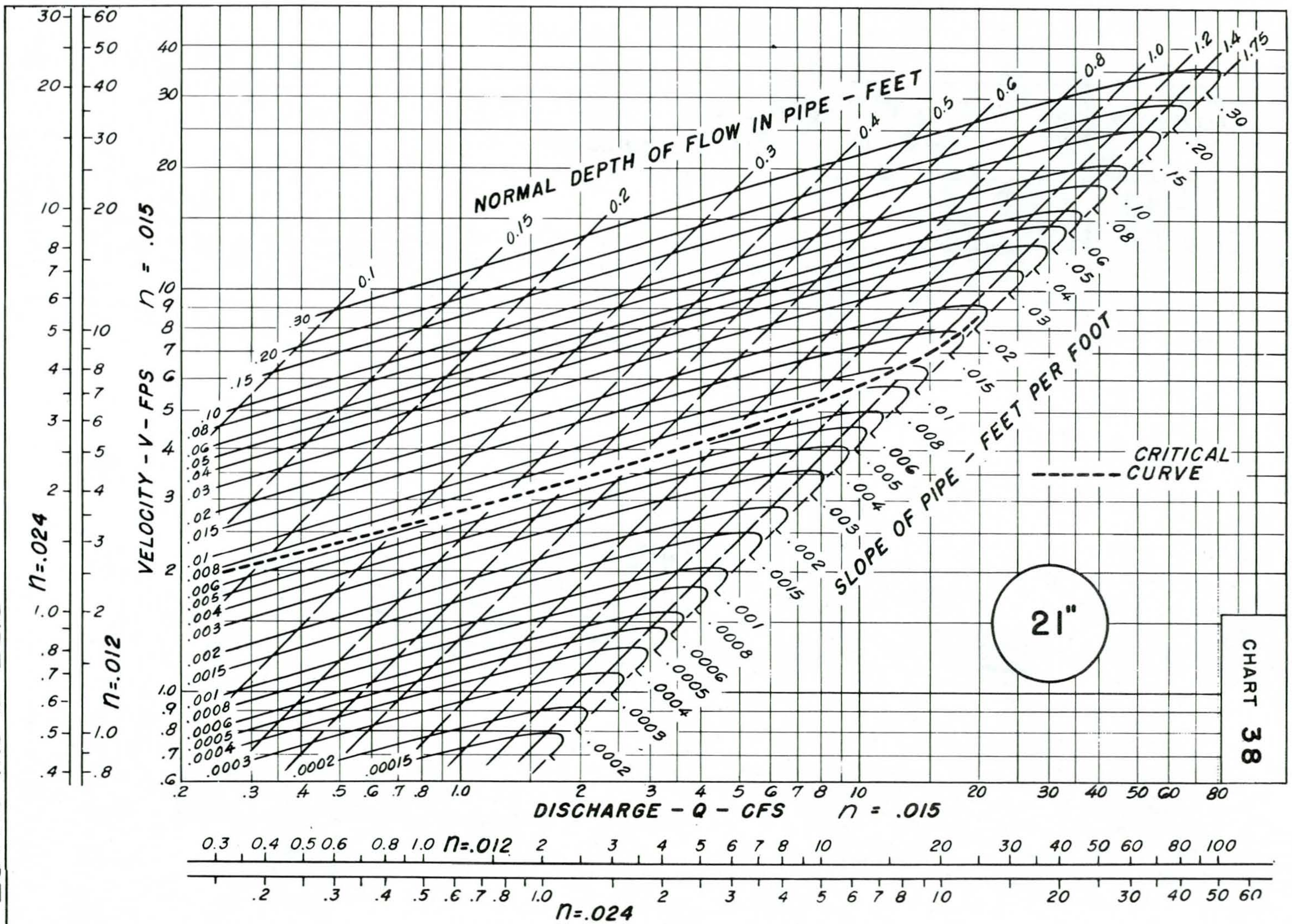
PIPE FLOW CHART
15-INCH DIAMETER



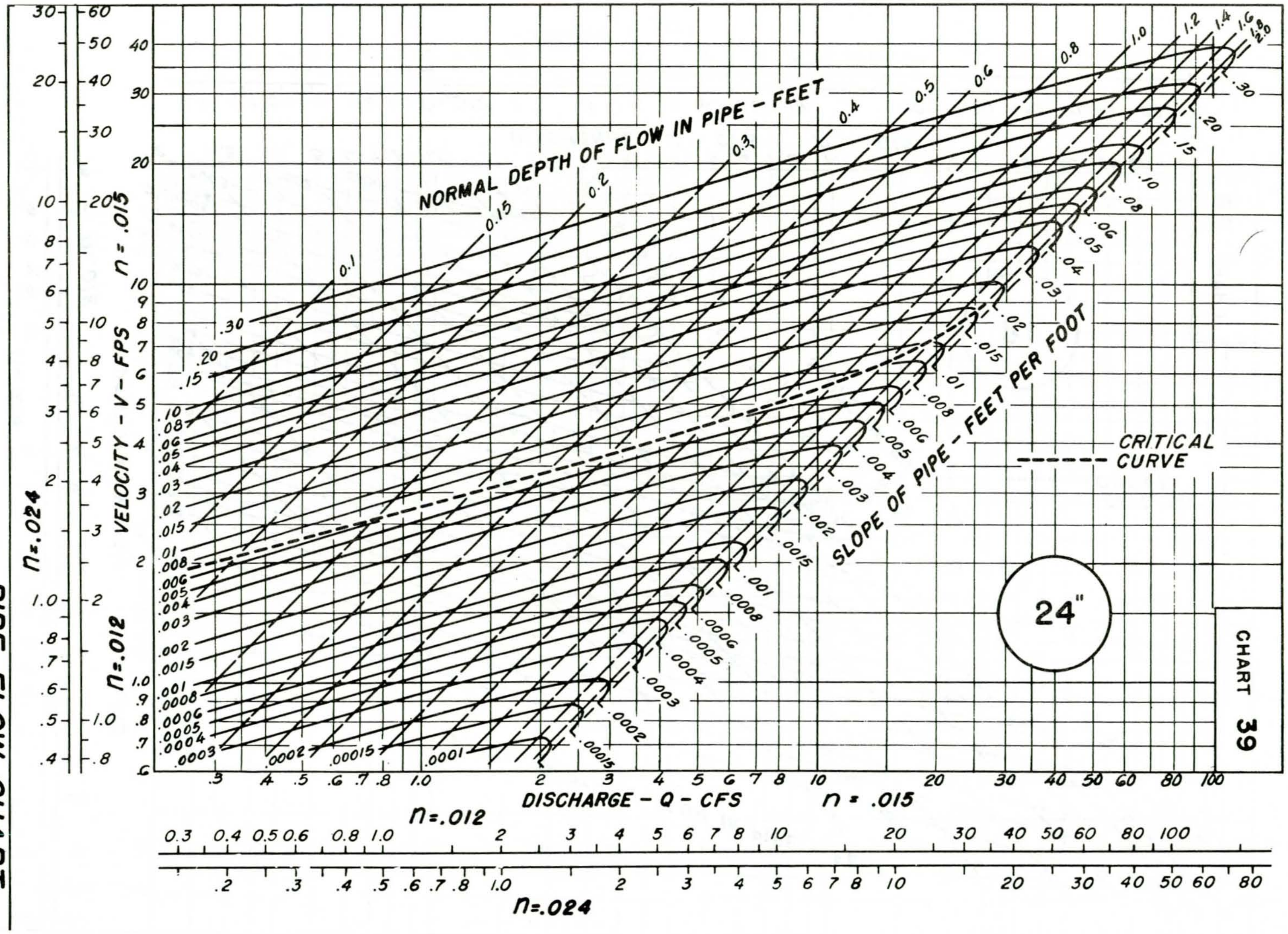


PIPE FLOW CHART
18-INCH DIAMETER

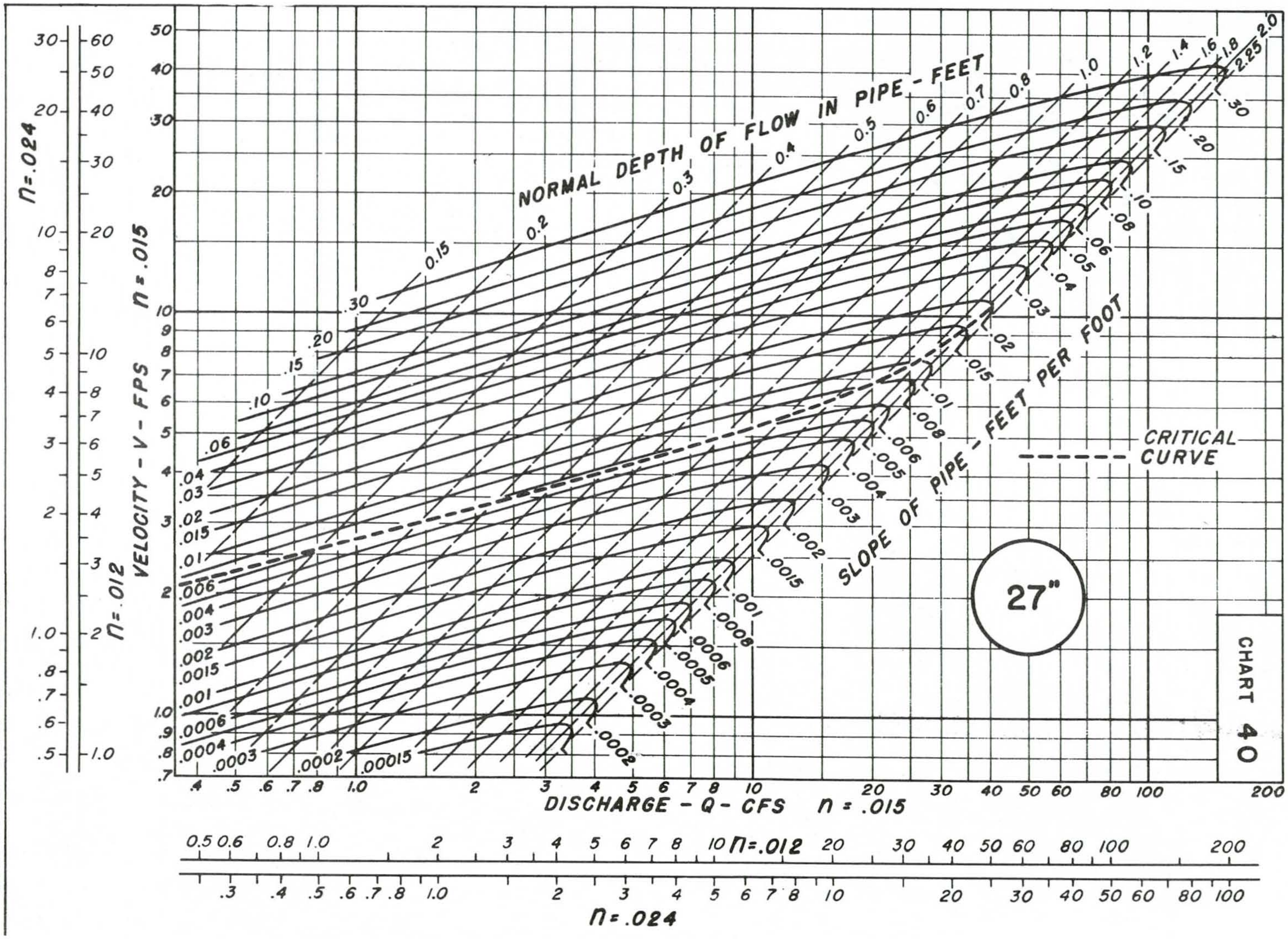
PIPE FLOW CHART 21-INCH DIAMETER

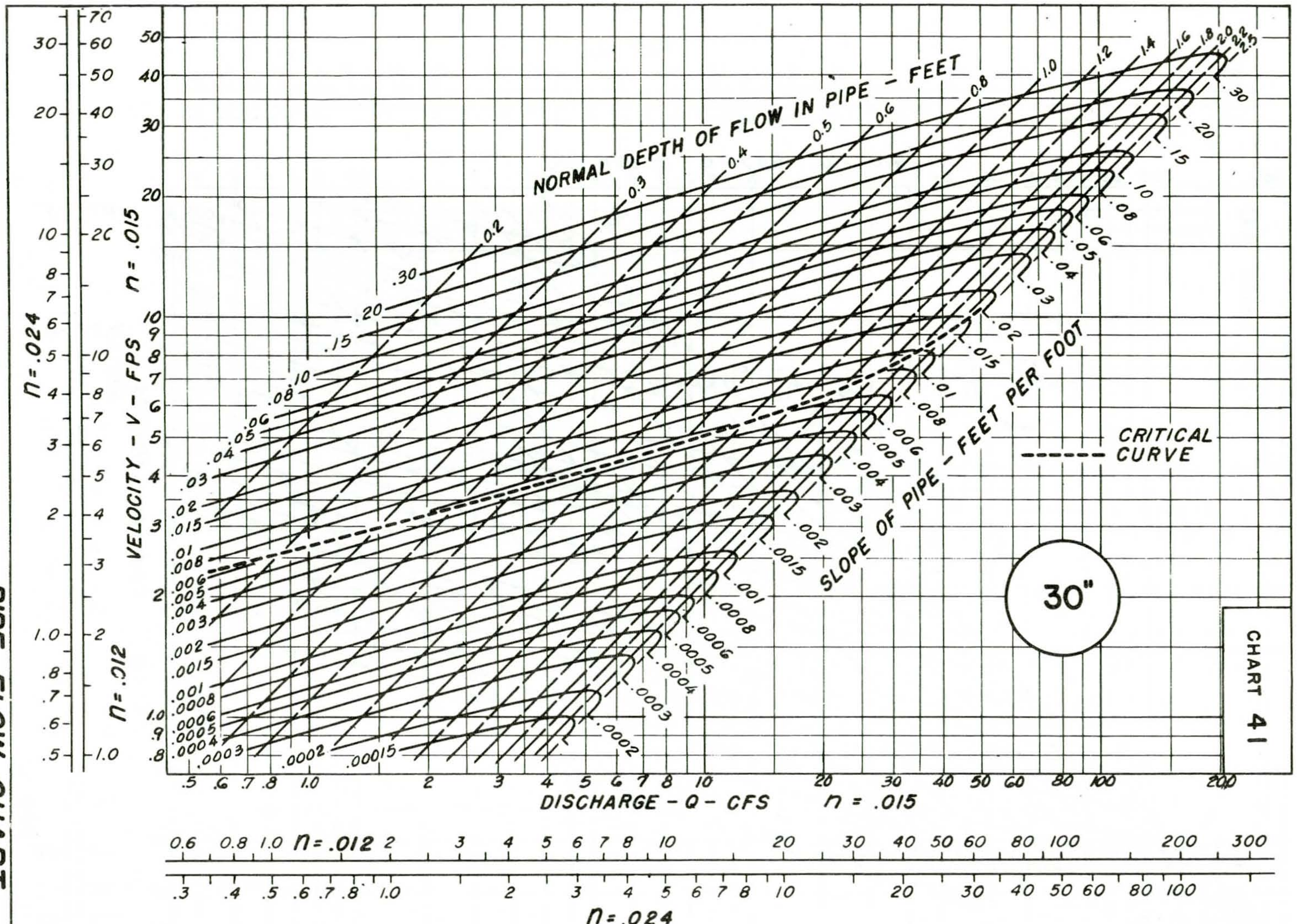


PIPE FLOW CHART
24-INCH DIAMETER



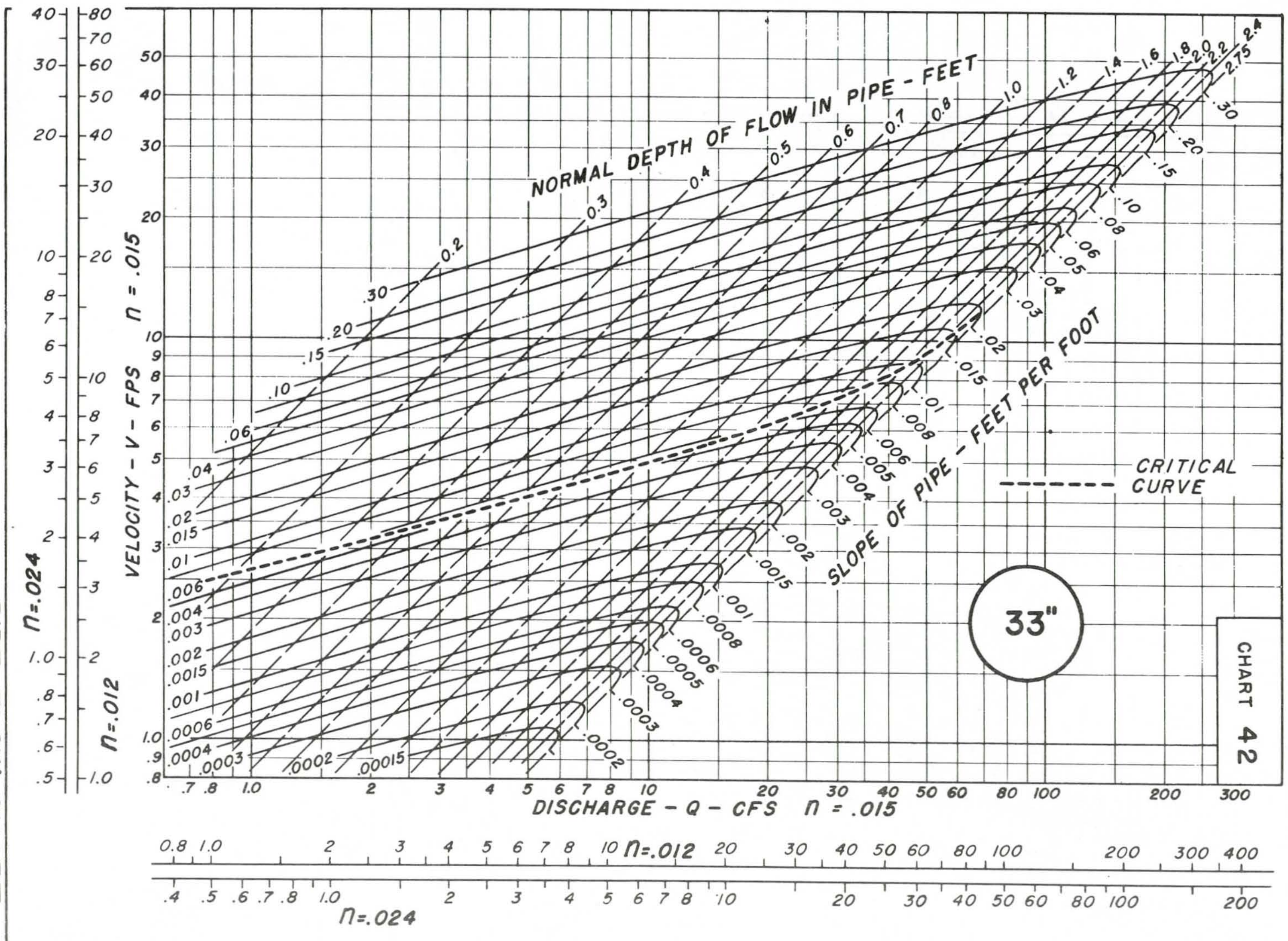
PIPE FLOW CHART
27-INCH DIAMETER



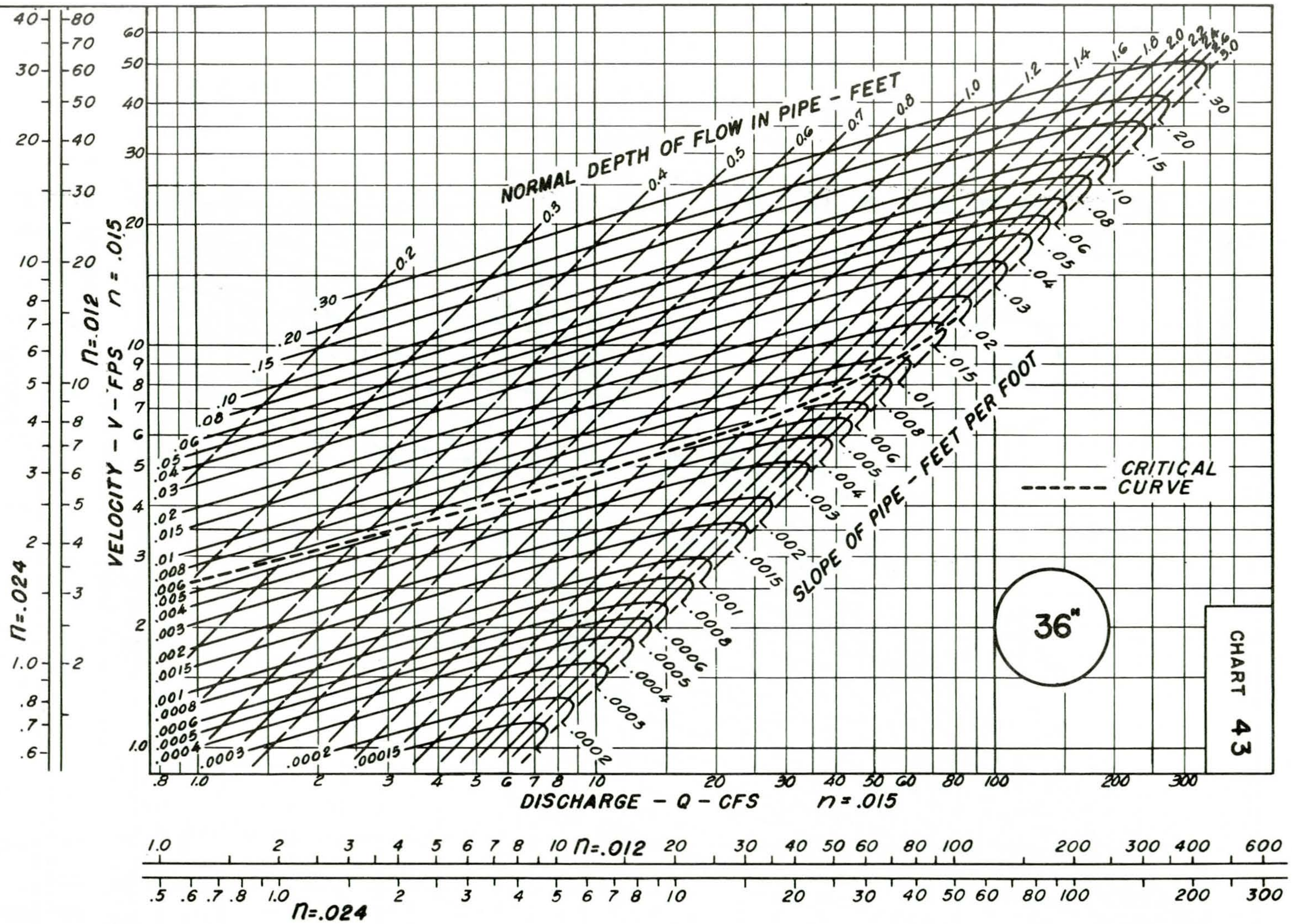


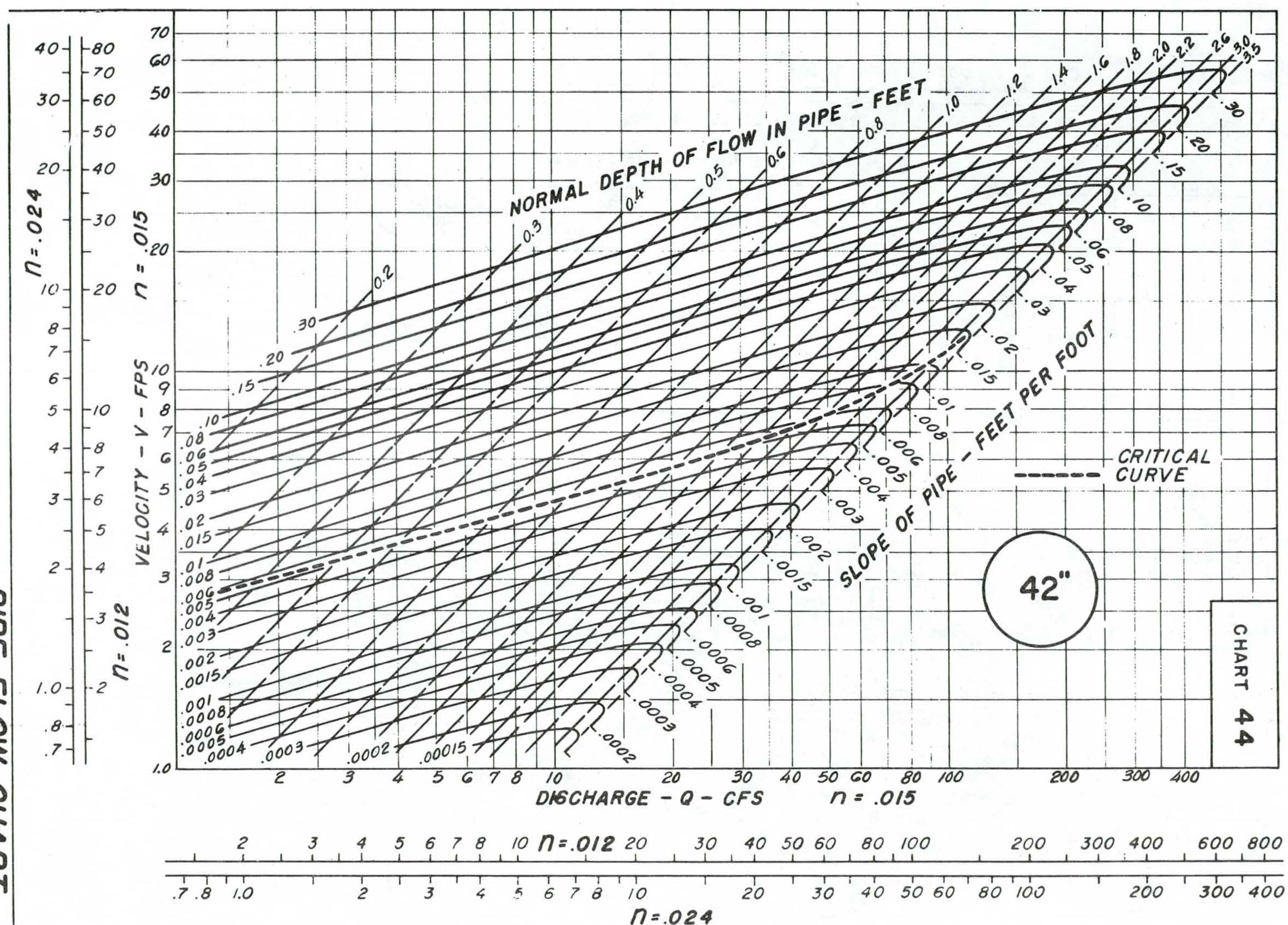
PIPE FLOW CHART
30-INCH DIAMETER

PIPE FLOW CHART
33-INCH DIAMETER

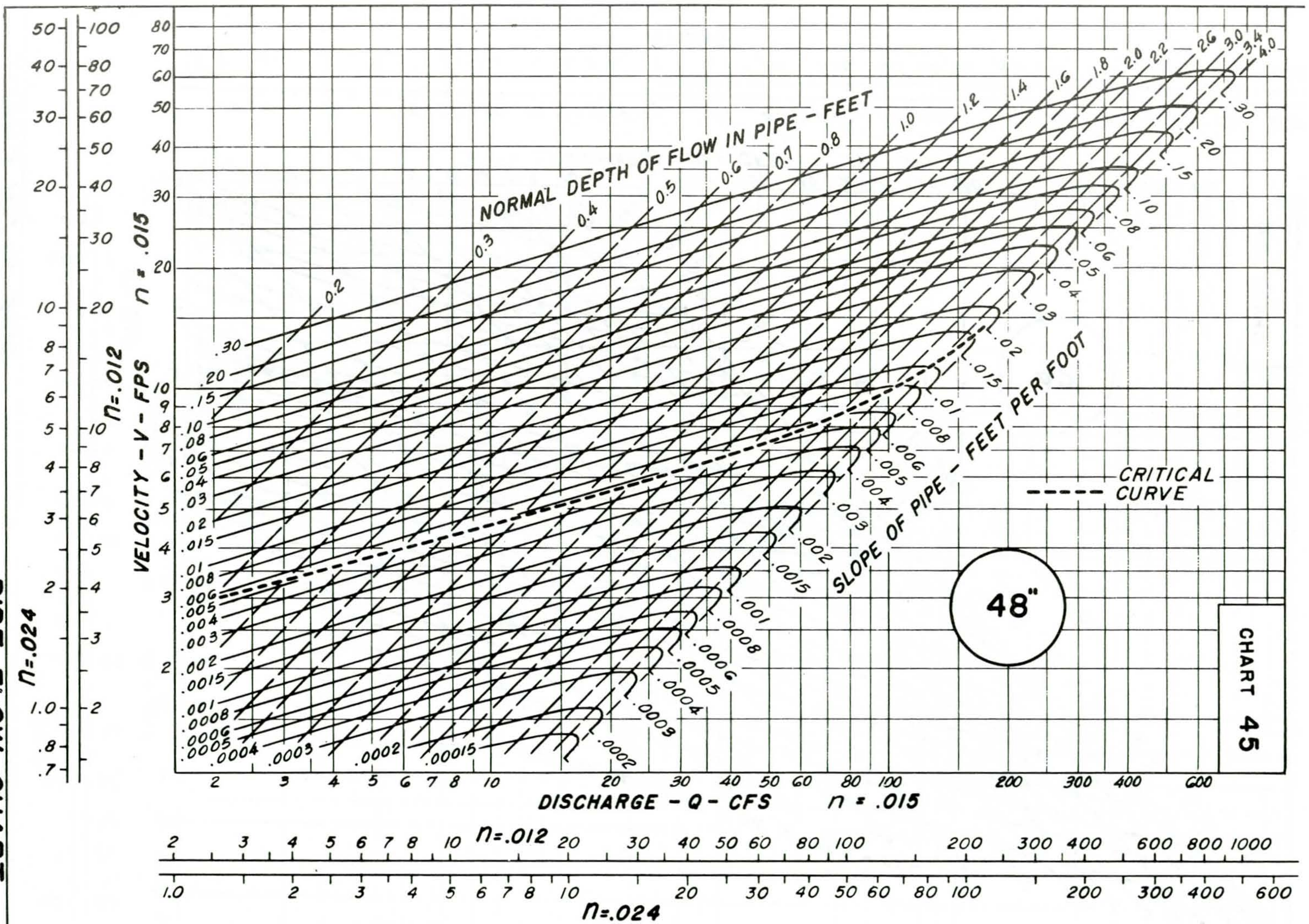


PIPE FLOW CHART
36-INCH DIAMETER



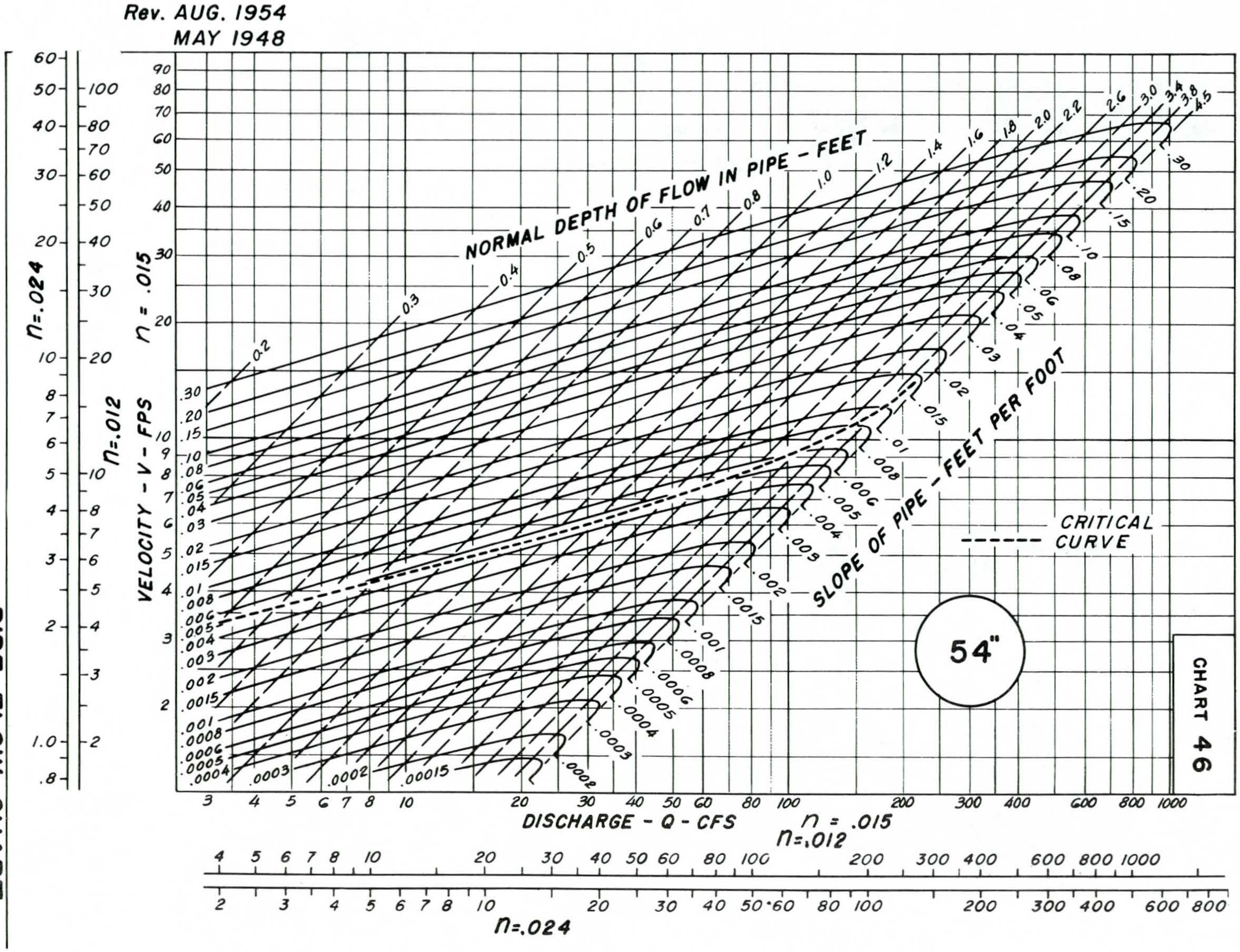


PIPE FLOW CHART
42-INCH DIAMETER

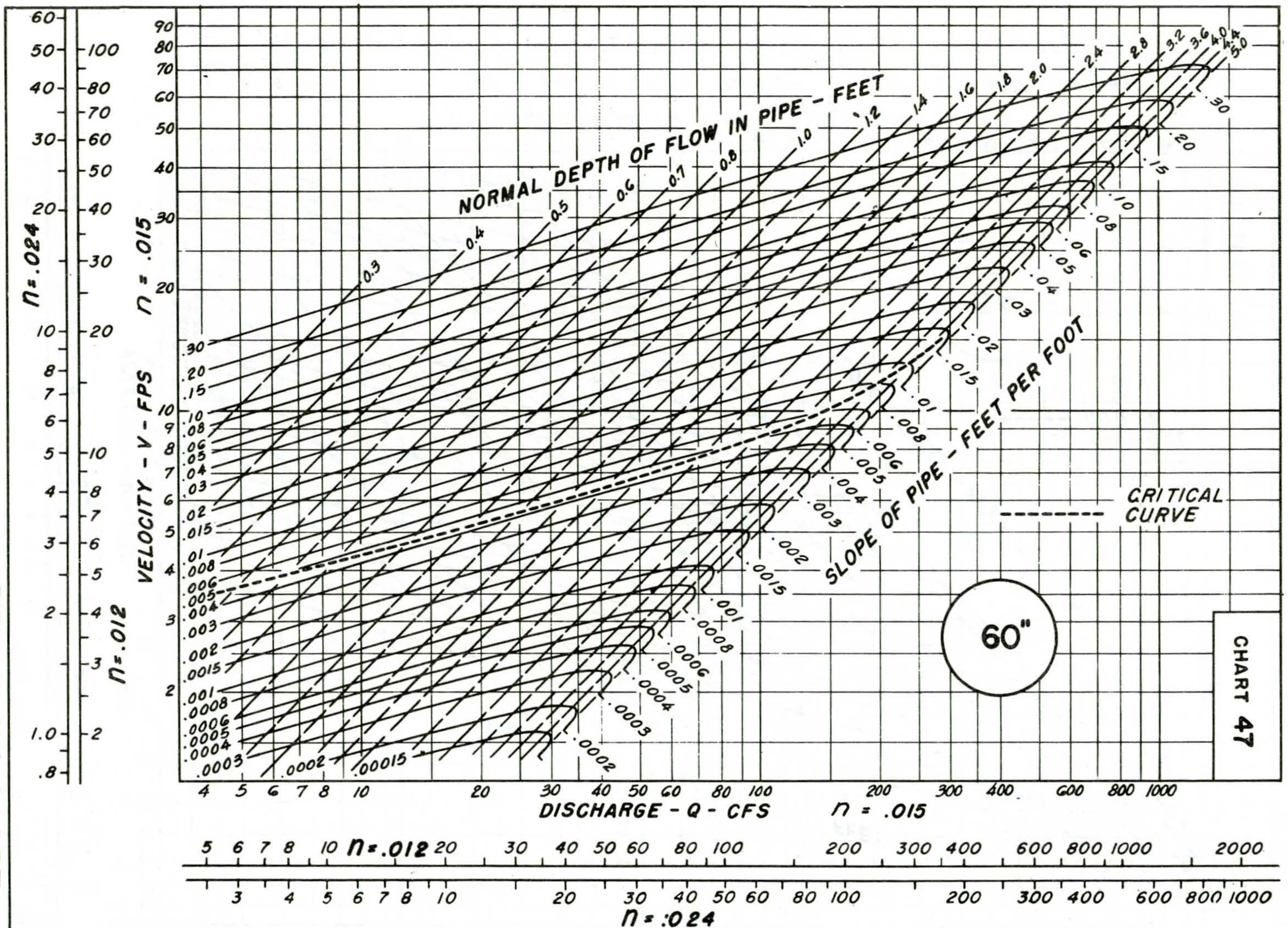


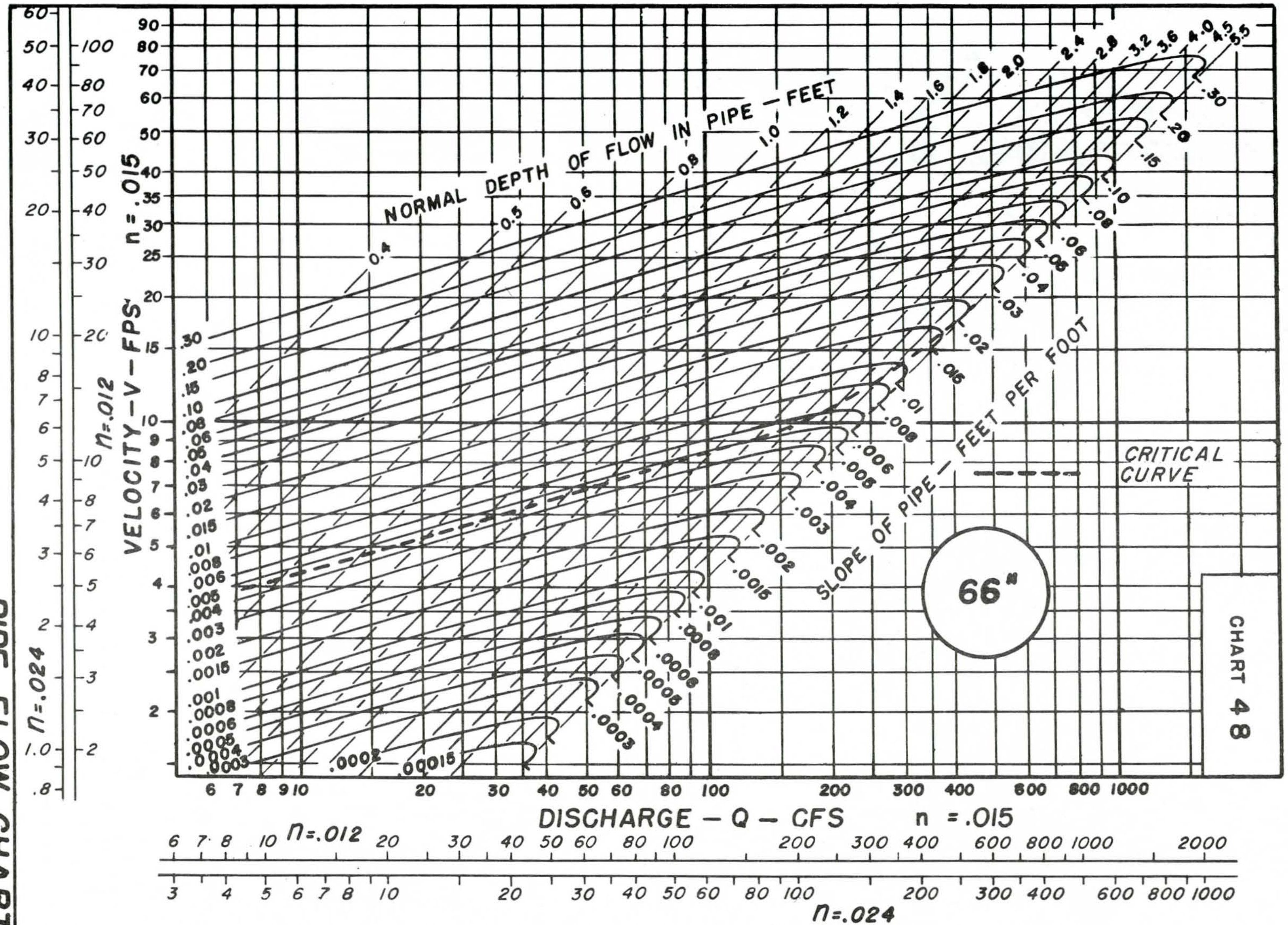
PIPE FLOW CHART
48-INCH DIAMETER

PIPE FLOW CHART
54-INCH DIAMETER

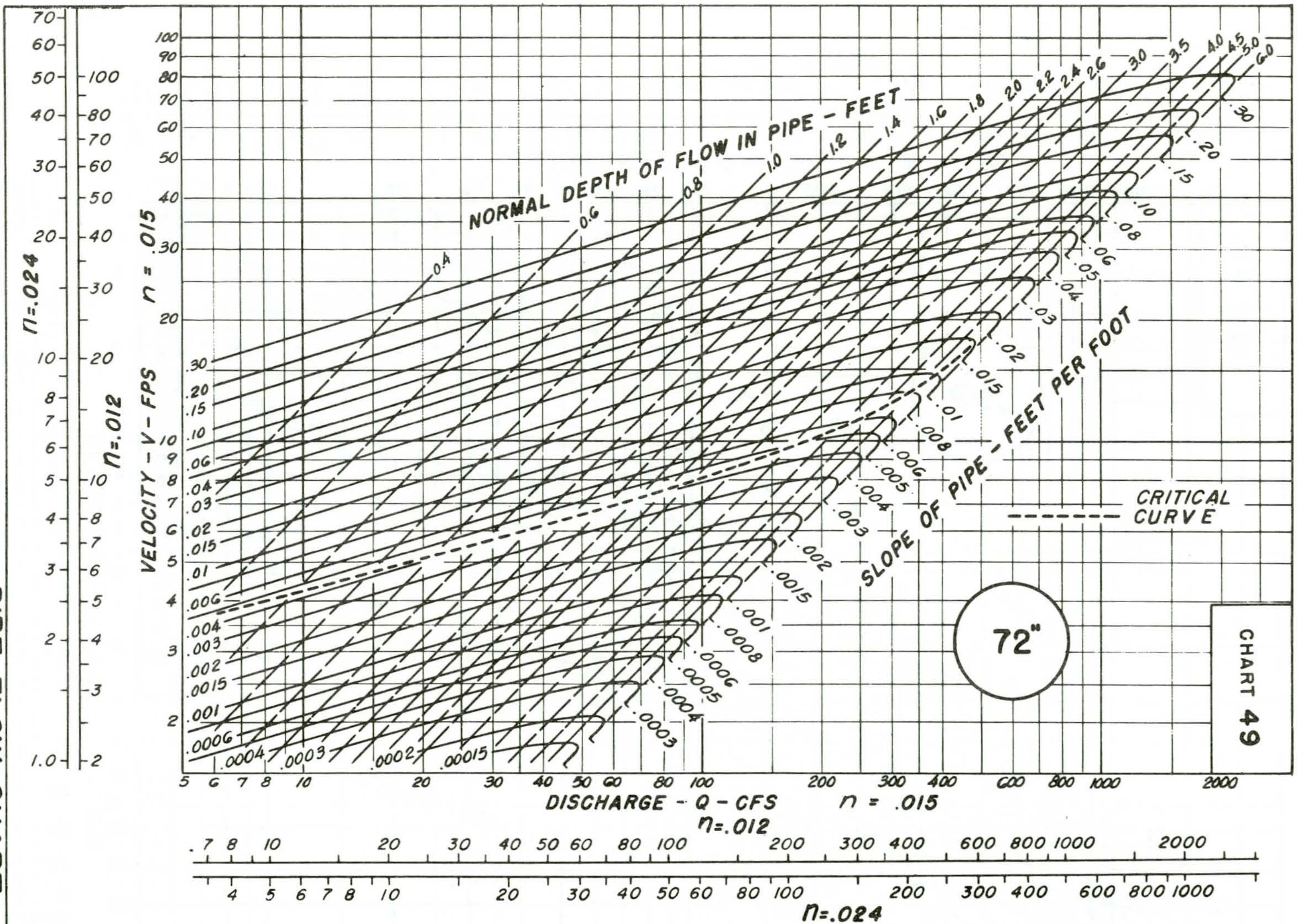


PIPE FLOW CHART
60-INCH DIAMETER



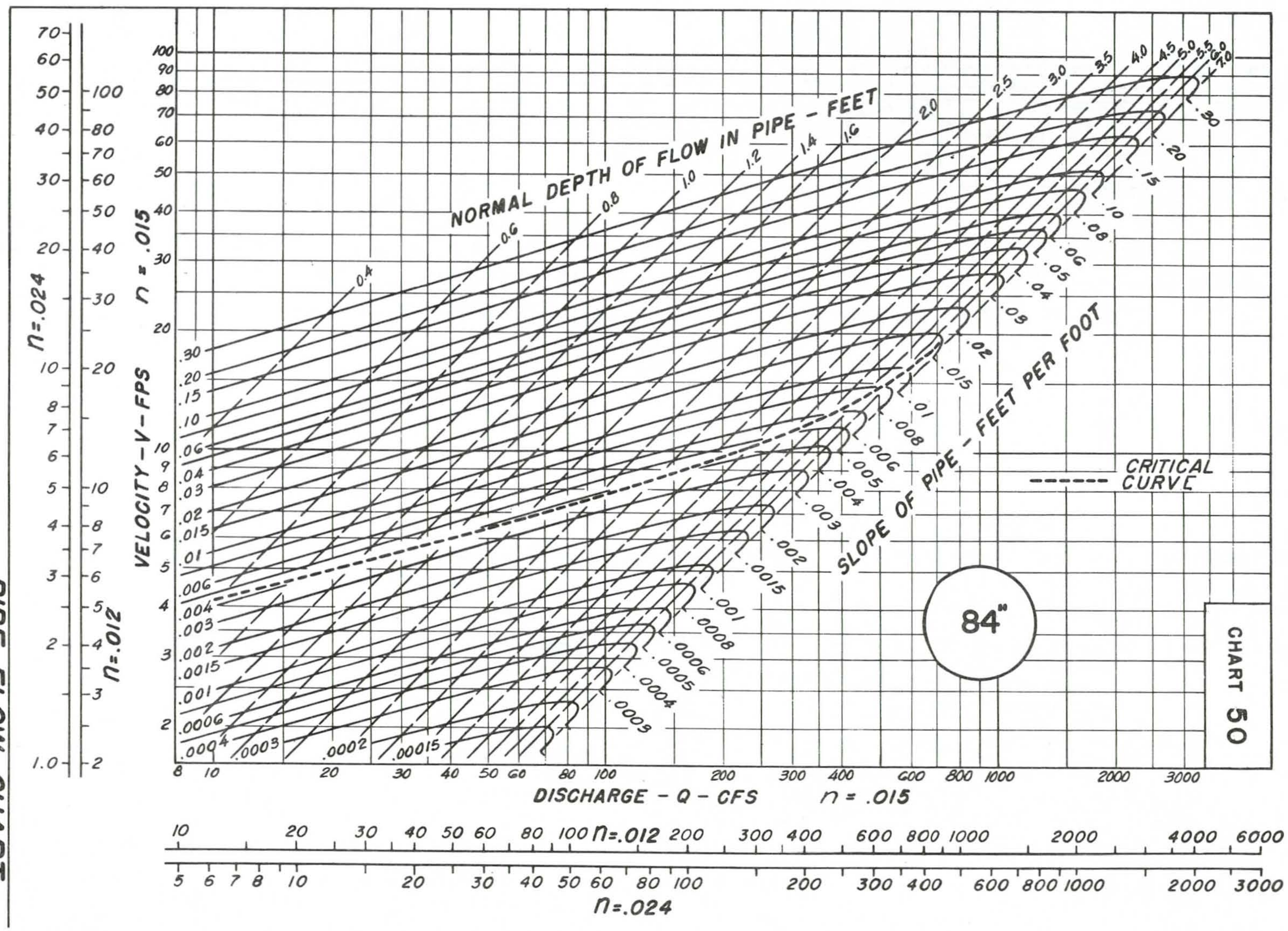


PIPE FLOW CHART
66-INCH DIAMETER



PIPE FLOW CHART
72-INCH DIAMETER

PIPE FLOW CHART
84-INCH DIAMETER



PIPE FLOW CHART
96-INCH DIAMETER

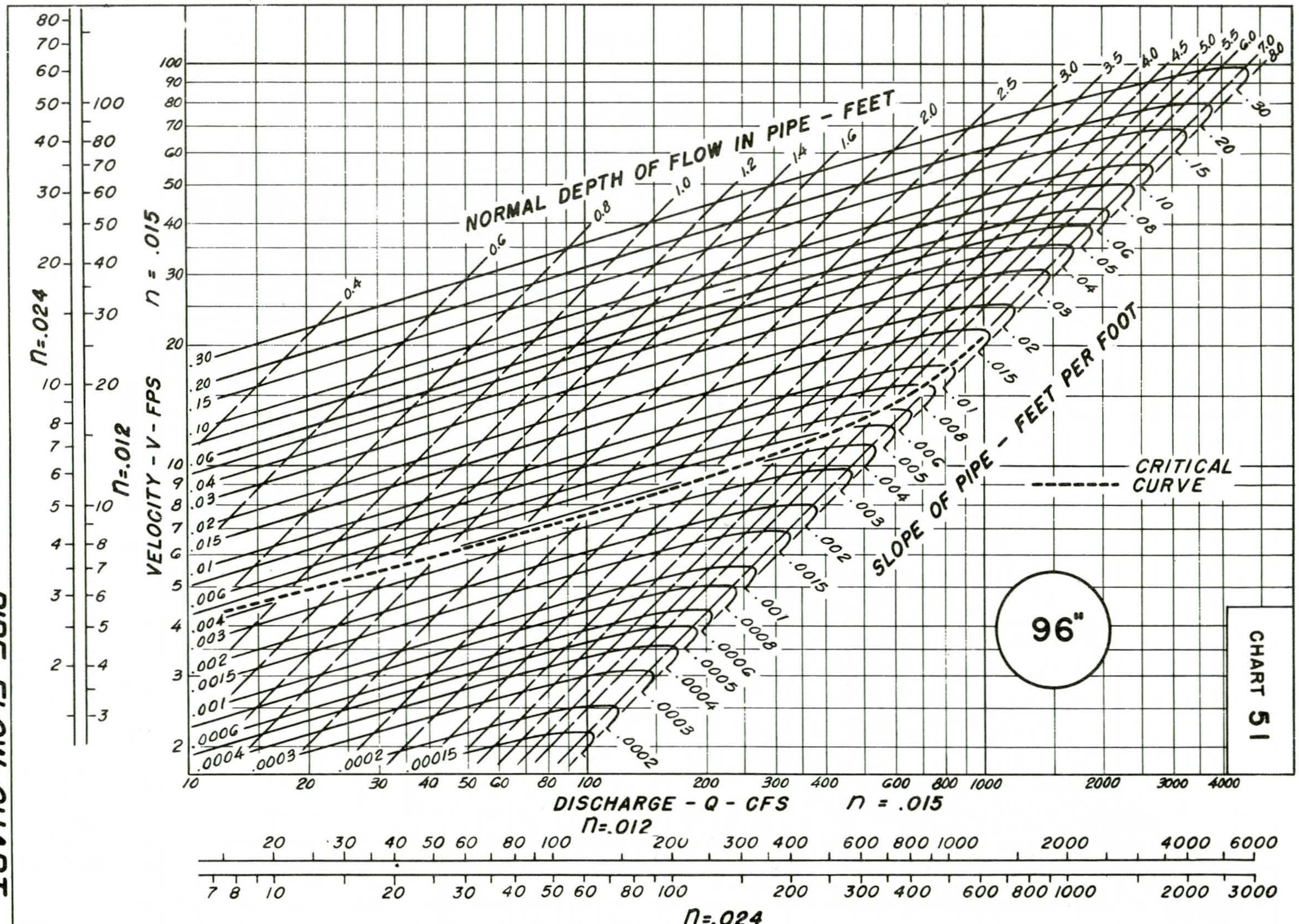
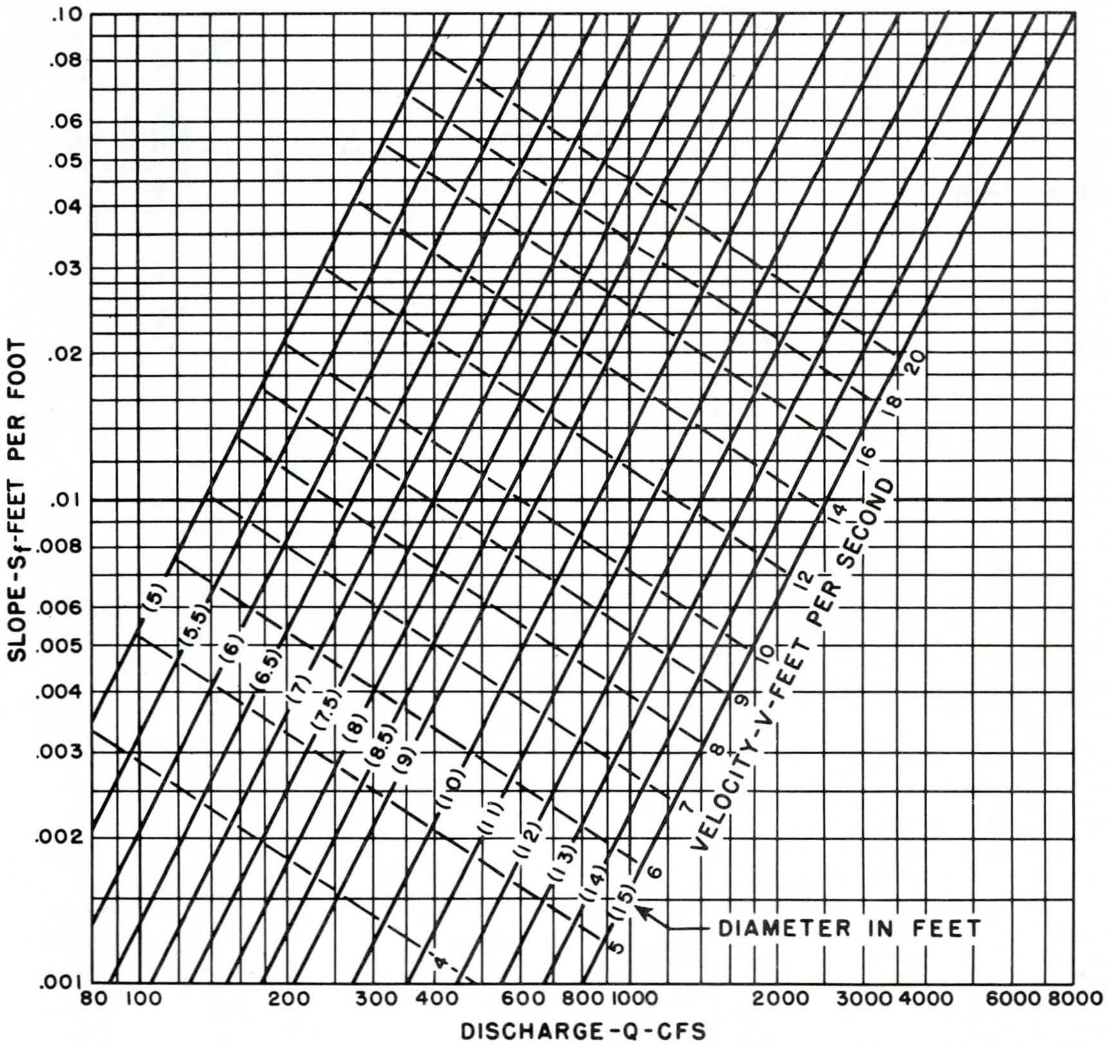
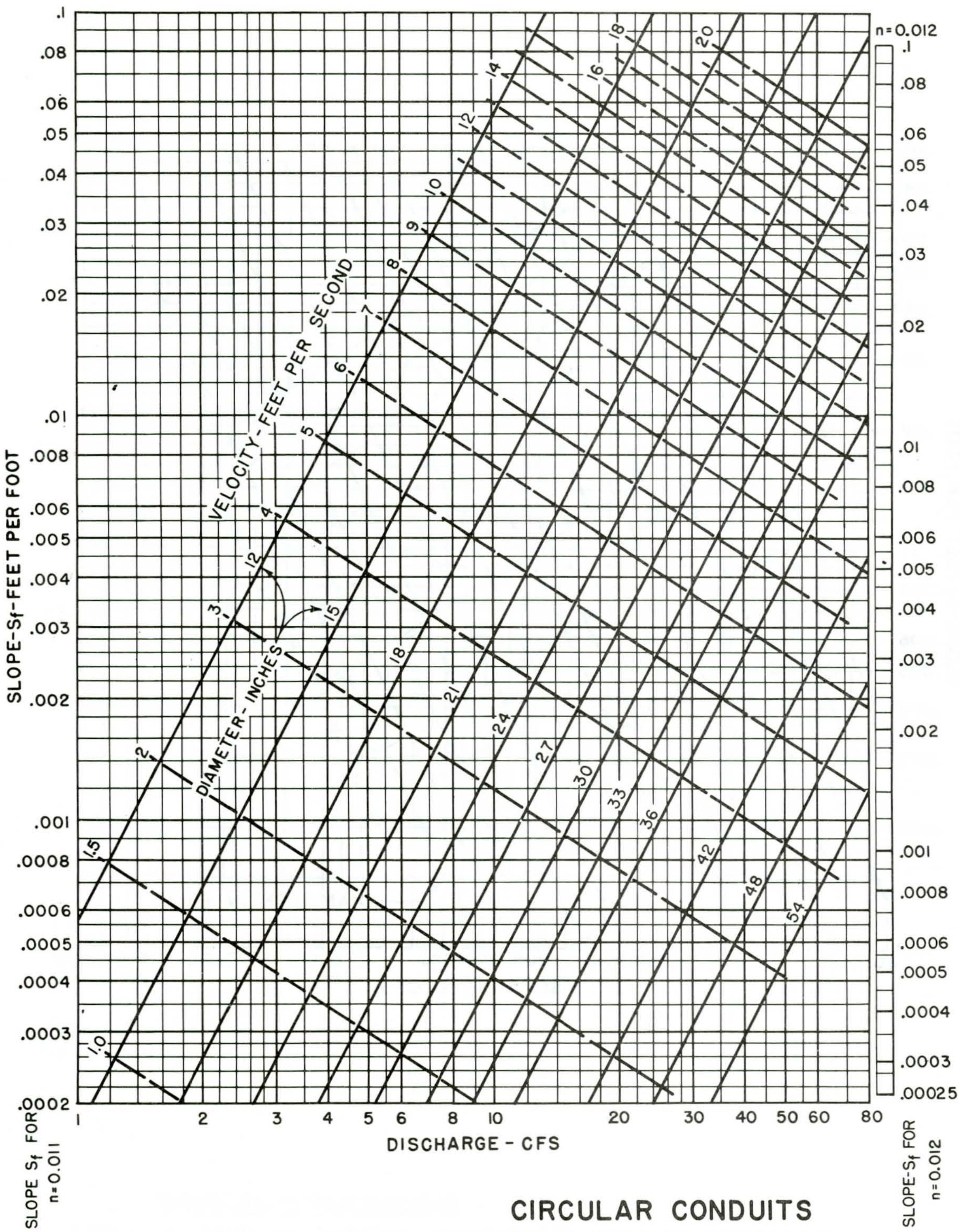


CHART 52



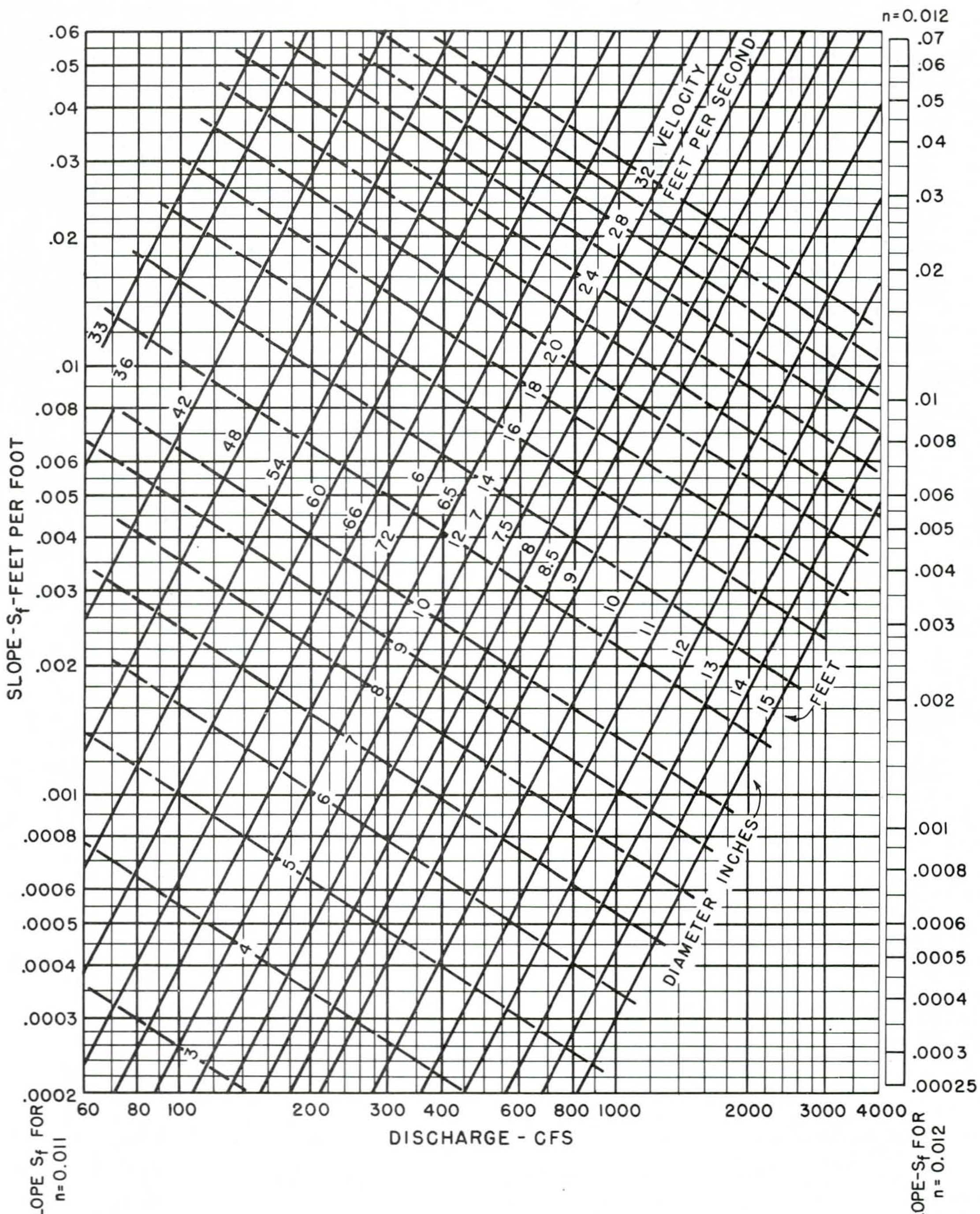
CIRCULAR C. M. PIPE
FRICTION SLOPE FLOWING FULL
n=0.025

CHART 53

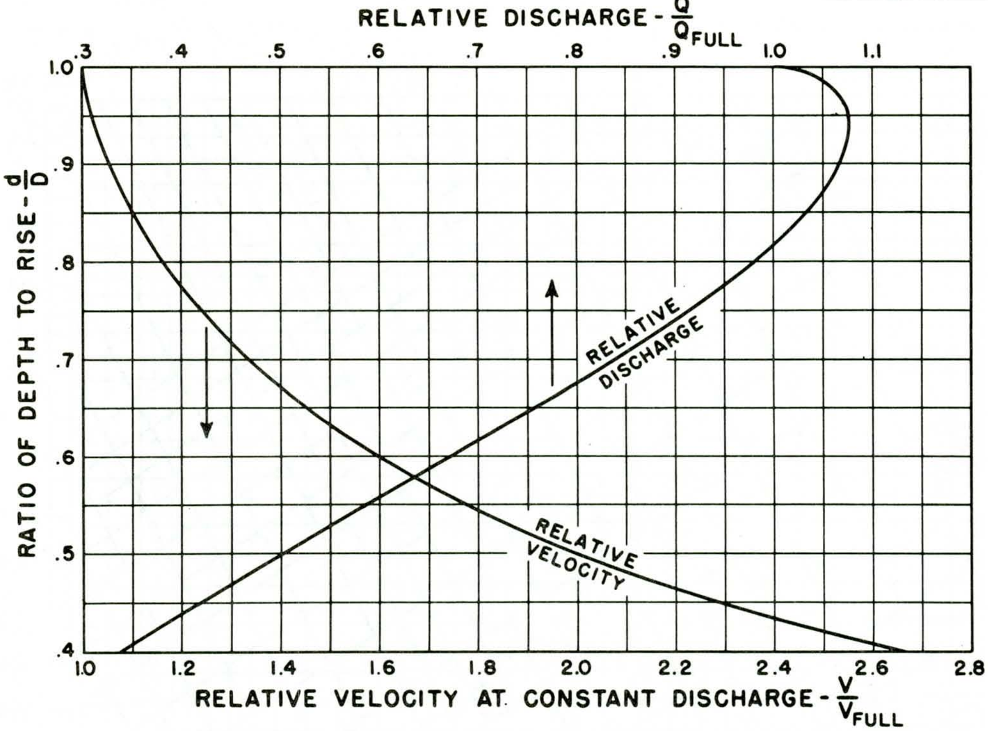


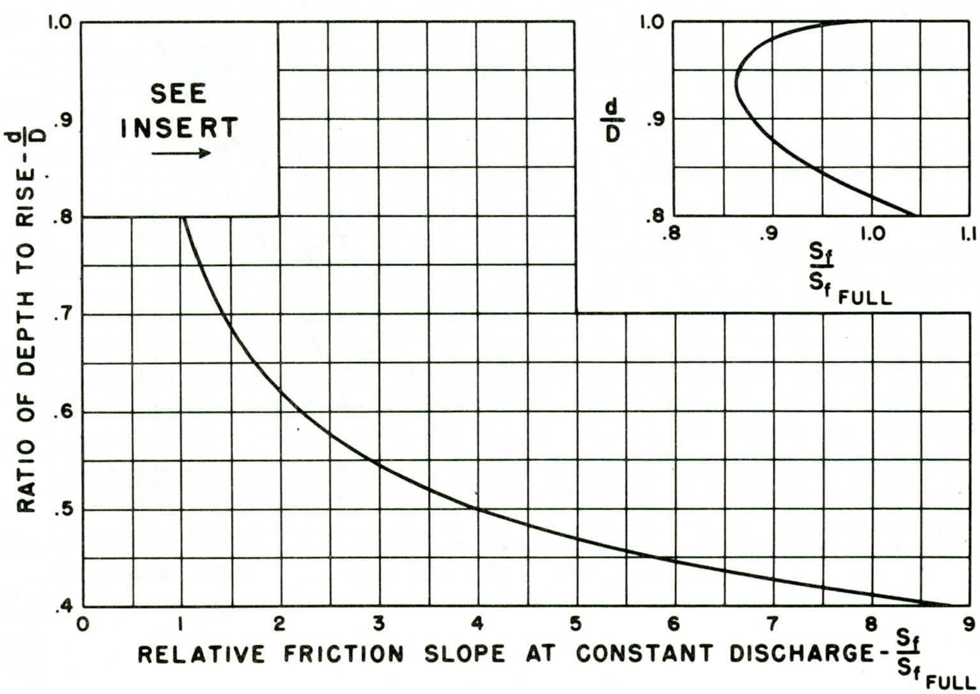
CIRCULAR CONDUITS
FRICTION SLOPE FLOWING FULL
n=0.011(and 0.012)

CHART 54



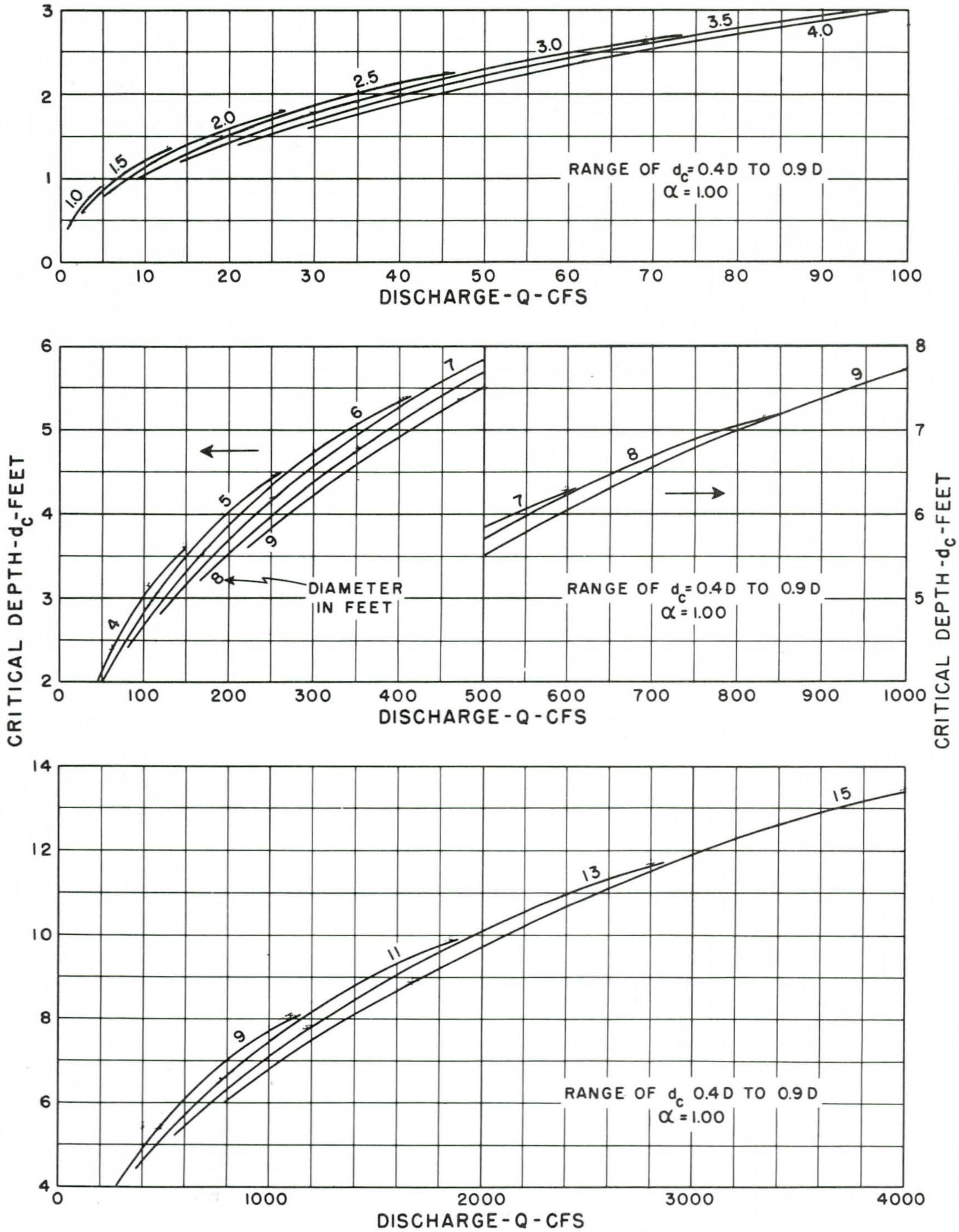
CIRCULAR CONDUITS
FRICTION SLOPE FLOWING FULL
n=0.011 (and 0.012)





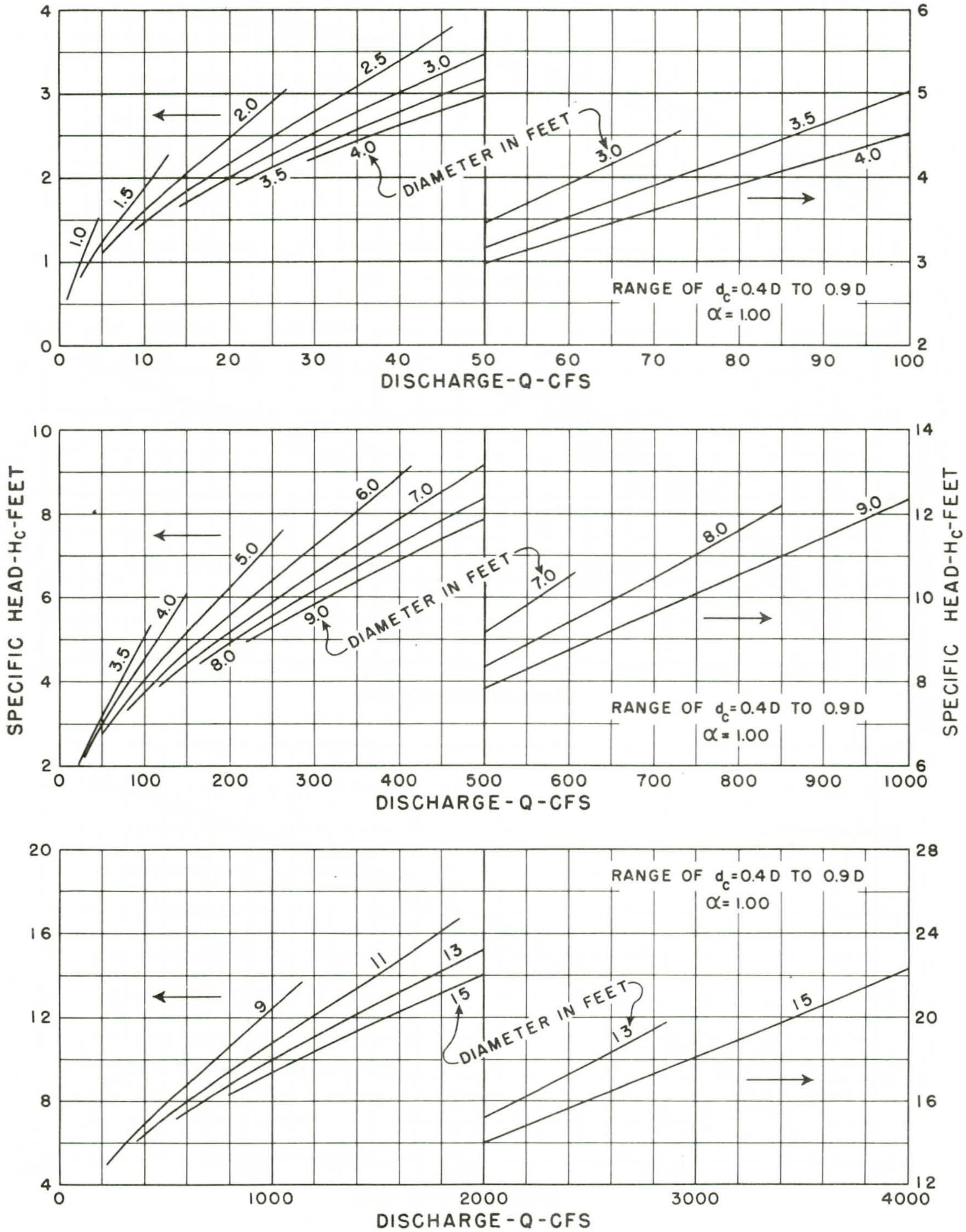
CIRCULAR PIPE
PART FULL FLOW

CHART 56



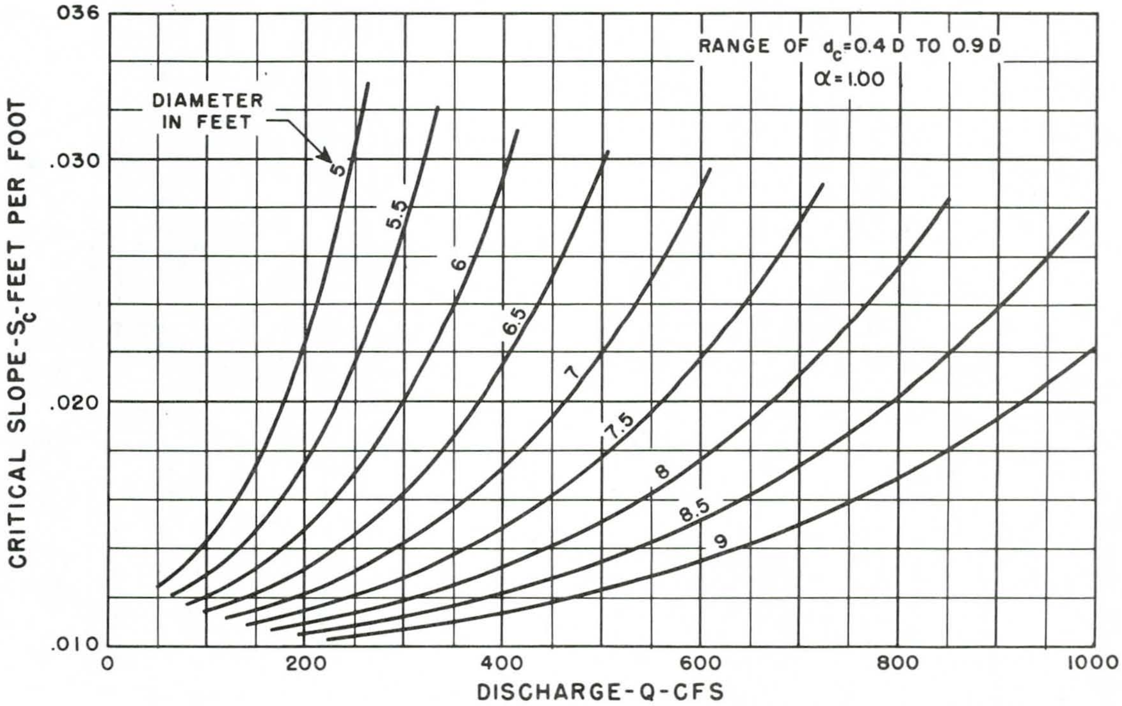
CIRCULAR PIPE
CRITICAL DEPTH

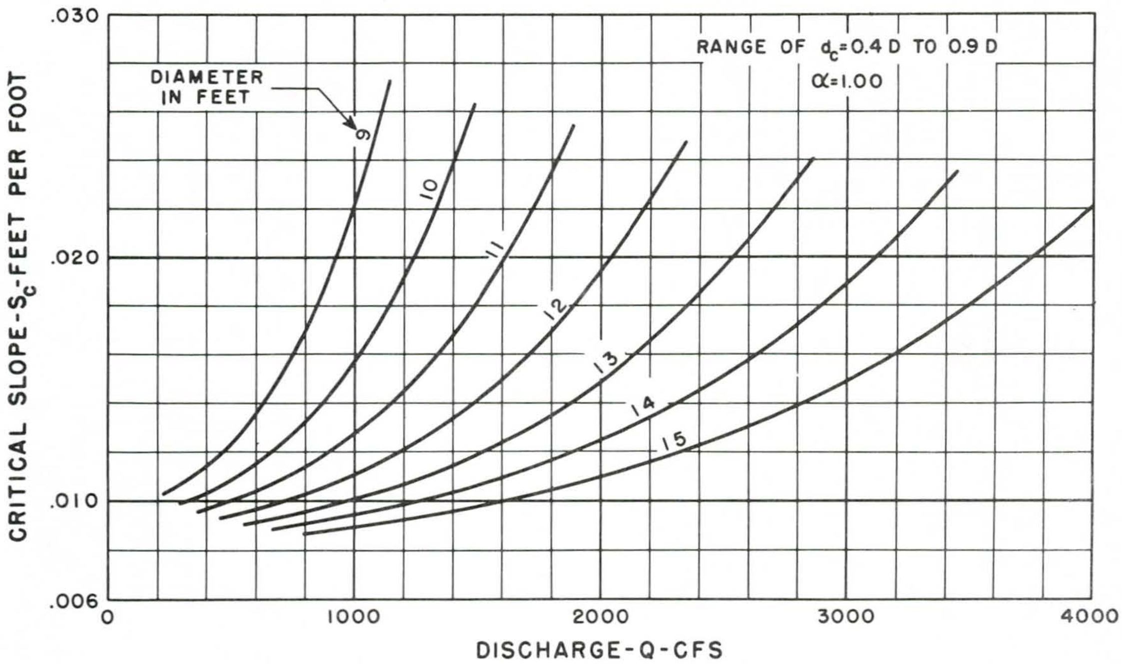
CHART 57



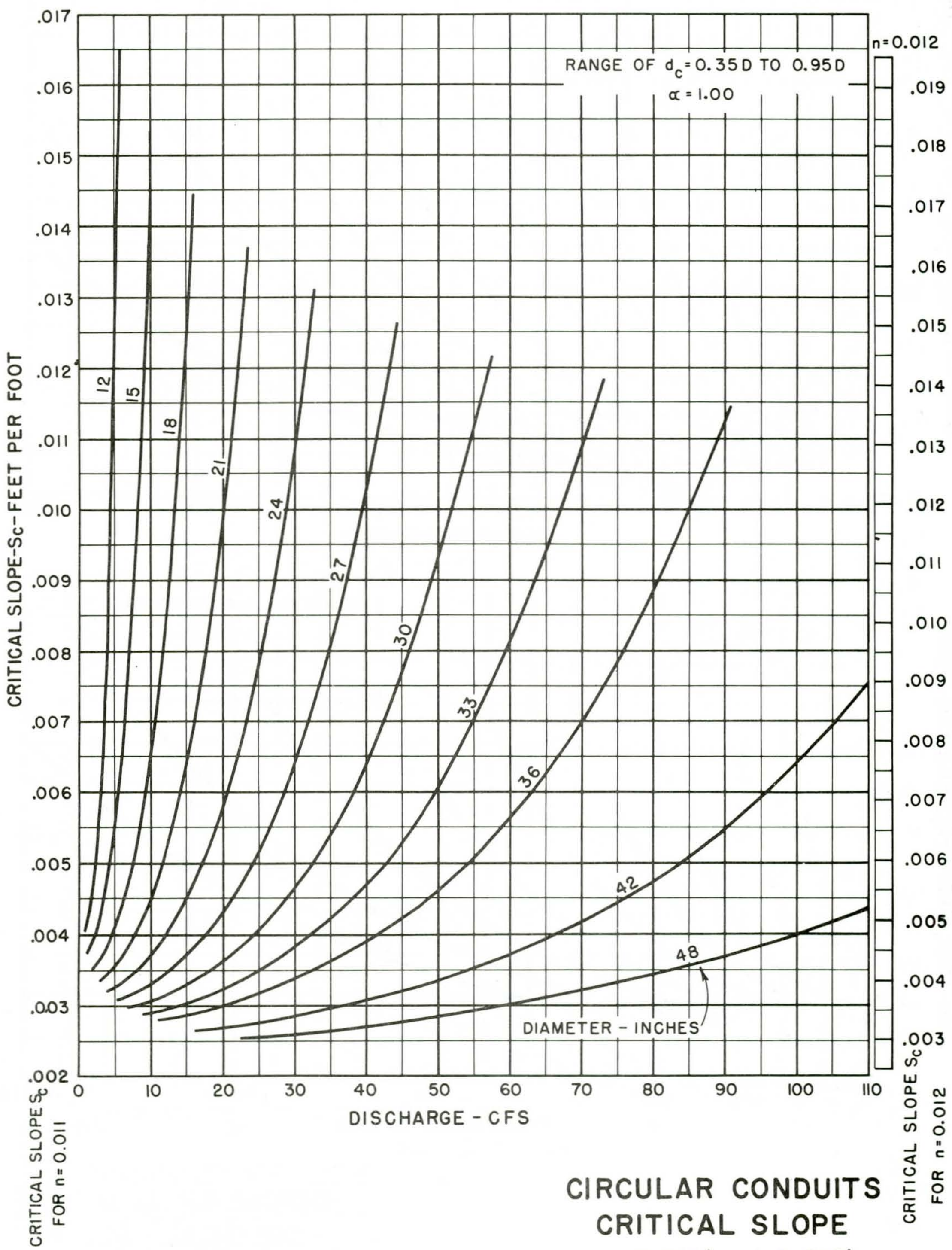
CIRCULAR PIPE
SPECIFIC HEAD AT CRITICAL DEPTH

CHART 58



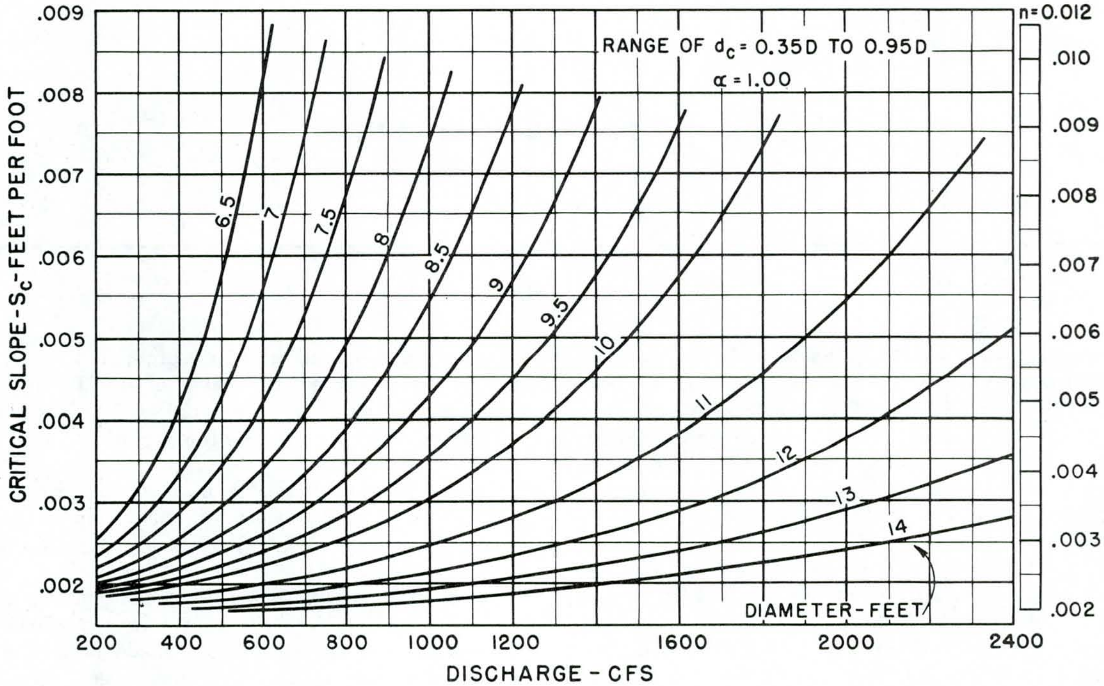


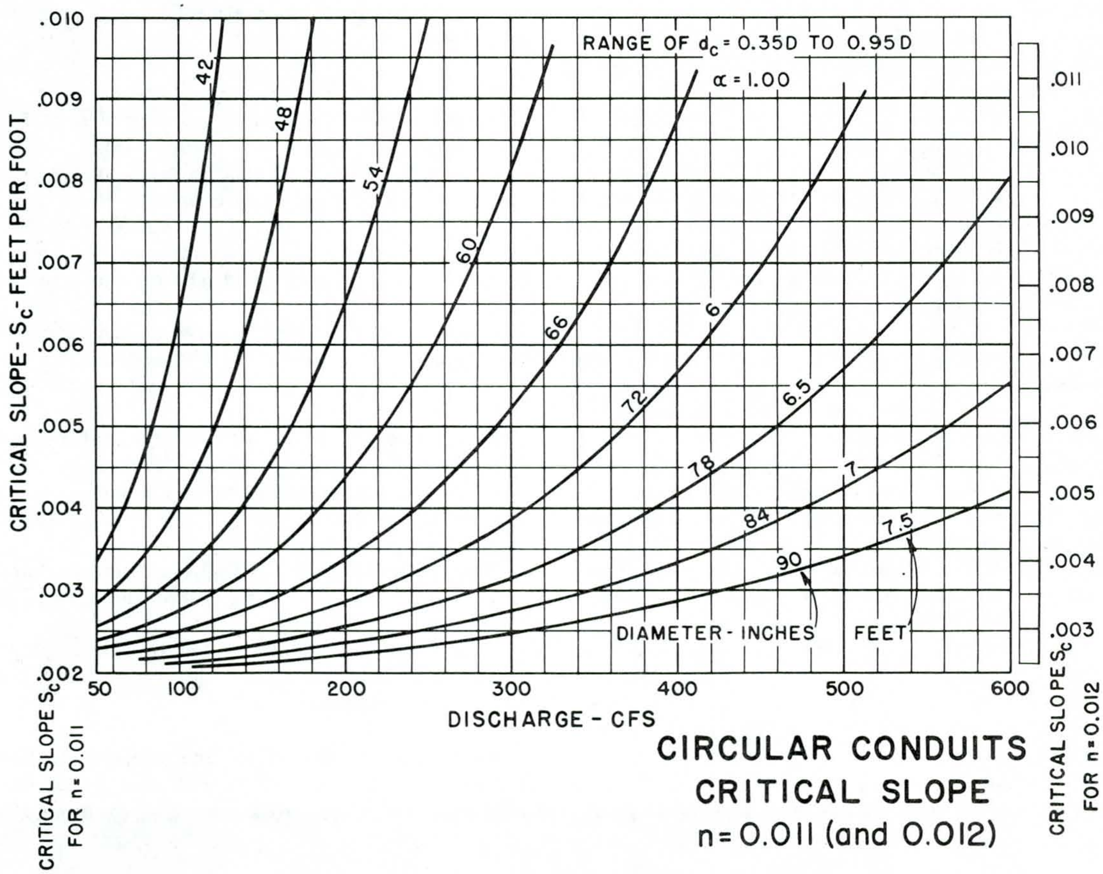
CIRCULAR C. M. PIPE
CRITICAL SLOPE
n = 0.025



CIRCULAR CONDUITS
CRITICAL SLOPE
n=0.011(and 0.012)

CHART 60





CIRCULAR CONDUITS CRITICAL SLOPE

n=0.011 (and 0.012)

Chapter 6.—PIPE-ARCH CHANNELS

6.1 Description of charts. Charts 61–73 are designed for use in the solution of the Manning equation for pipe-arch channels which have sufficient length, on constant slope, to establish uniform flow at normal depth without backwater or pressure head. It is important to recognize that they are not suitable for use in connection with most types of culvert flow, since culvert flow is seldom uniform. The charts are in three groups:

Group 1.—Charts 61–65 are for standard sizes of riveted, corrugated-metal pipe-arches ($n=0.024$), varying from 25 by 16 inches to 72 by 44 inches in cross section.

Group 2.—Charts 66–68 are for the same sizes of pipe-arches as those in group 1, but group 2 pipe-arches have 40-percent paved inverts ($n=0.019$). Charts 63 and 64 of group 1 are also used with group 2 charts to compute critical depth and specific head at critical depth.

Group 3.—Charts 69–73 are for standard sizes of field-bolted corrugated-metal pipe-arches ($n=0.025$) ranging in cross section from 6 feet, 1 inch, by 4 feet, 7 inches, to 16 feet, 7 inches, by 10 feet, 1 inch.

These charts are similar to charts 52–60, described in chapter 5. They require the use of several charts for solving the Manning equation. Each group of charts consists of a chart showing friction slope, discharge, and velocity for full flow; a chart of ratios for computing part-full flow; and charts for computing critical flow.

6.2 Instructions for use of charts 61–73. One set of instructions applies to all of the three groups comprising charts 61–73. Separation into groups is made because of differences in n values of groups 1 and 2 and differences in both sizes and n value of group 3. Charts 63 and 64 are common to groups 1 and 2 because they are used to find critical depth and specific head at critical depth, and both of these are independent of the value of n.

It will be noted that charts 69–73 for field-bolted pipe-arches are based on $n=0.025$. For 6-inch by 2-inch corrugations, current laboratory tests indicate that the value of n should be higher. When the final results of these tests are published, the user may wish to add a slope scale for the new value of n to charts 69 and 73. Such scales could be placed as are the $n=0.012$ scales on charts 53 and 59 of chapter 5.

The use of charts 61–73 requires, first, finding the friction slope for the given discharge in a pipe flowing full, by using chart 61, 66, or 69 (for group 1, 2, or 3, respectively), depending on the value of n. Then the ratio graphs of chart 62, 67, or 70 (for group 1, 2, or 3, respectively) are used to find solutions for discharge Q, depth d, velocity V, and friction slope S_f.

Critical depth d_c, specific head H_c at critical depth, and critical slope S_c are determined from charts 63–65 (for group 1), 63, 64, and 68 (for group 2), or 71–73 (for group 3).

In the more specific instructions that follow, whenever the choice among three different charts is specified, it is understood that the selection is made according to the appropriate group 1, 2, or 3, in that order. For example, in the first step described in the next subsection, chart 61 is used for group 1, chart 66 for group 2, and chart 69 for group 3.

6.2–1 Use of charts to find discharge. The following steps are used to find discharge, when depth of flow and slope of pipe are known (see example 18).

First find full-flow discharge Q_{FULL} corresponding to the slope of the pipe, using chart 61, 66, or 69.

Next compute the ratio of depth of flow to rise of pipe, d/D, and on chart 62, 67, or 70 read the corresponding Q/Q_{FULL} from the relative discharge curve in the upper graph.

Finally, compute the discharge at the given depth by multiplying the full-flow discharge (from the first step) by the ratio Q/Q_{FULL} (from the second step).

6.2–2 Use of charts to find depth of uniform flow. The following steps are used to find depth of uniform flow, when discharge and slope are known (see example 19).

Find Q_{FULL} corresponding to the slope of the pipe, using chart 61, 66, or 69.

Next compute the ratio Q/Q_{FULL}, and on chart 62, 67, or 70 read the corresponding d/D on the relative discharge curve in the upper graph.

Finally, compute depth of flow by multiplying the rise of the arch D by d/D (from the second step). D and d must be in the same units.

6.2–3 Use of charts to find velocity of flow. The following steps are used to find velocity of flow, when discharge and slope are known (see example 19).

First find V_{FULL} corresponding to the given discharge rate, using chart 61, 66, or 69.

If the depth of flow is unknown, determine it according to the instructions in section 6.2–2.

Next compute the ratio d/D and on chart 62, 67, or 70 read the corresponding V/V_{FULL} on the relative velocity curve in the upper graph.

Finally, compute the mean velocity V of part-full flow by multiplying V_{FULL} by the ratio V/V_{FULL}.

6.2–4 Use of charts to find slope required to maintain flow. The following steps are used to find slope required to maintain flow, when discharge and depth are known (see example 20).

First find $S_{f\ FULL}$ corresponding to the given discharge, using chart 61, 66, or 69.

Next compute the ratio d/D and on chart 62, 67, or 70 read the corresponding relative friction slope $S_f/S_{f\ FULL}$ on the lower graph.

Finally, compute friction slope S_f by multiplying $S_{f\ FULL}$ by the ratio $S_f/S_{f\ FULL}$.

6.2–5 Use of charts to find critical flow. The following steps are used to find critical flow (see example 21).

Critical depth d_c is read on chart 63 or 71 at the intersection of Q and the size of pipe-arch.

Minimum specific head H_c is read on chart 64 or 72 at the intersection of Q and the size of pipe-arch.

Critical slope S_c is read on chart 65, 68, or 73 at the intersection of Q and the size of pipe-arch.

Example 18

Given: A long pipe-arch, 58 by 36 in. in cross section, with $n=0.024$, on a 1.0-percent slope ($S=0.01$), flowing at a depth of 2.4 ft. *Find:* Discharge.

1. Group 1 charts are used. On chart 61, at the intersection of $S=0.01$ and the line for the 58 by 36-in. pipe-arch, read $Q_{FULL}=65$ c.f.s.
2. The ratio $d/D=2.4/3.0=0.8$. On the upper graph of chart 62, from the intersection of this value and the relative discharge curve, read the relative discharge$=1.02$.
3. Then $Q=65\times1.02=66$ c.f.s.

Example 19

Given: A long pipe-arch, 72 by 44 in. in cross section, with 40-percent paved invert, $n=0.019$, on a 1.8-percent slope ($S=0.018$), discharging 110 c.f.s. *Find:* Depth and velocity.

1. Group 2 charts are used. On chart 66 read $Q_{FULL}=$ 200 c.f.s.
2. The ratio $Q/Q_{FULL}=110/200=0.55$. In the upper graph of chart 67, from the intersection of this ratio value and the relative discharge curve, read $d/D=0.39$.
3. Then $d_n=0.39\times44/12=1.43$ ft.
4. On chart 66, from the intersection for $Q=110$ c.f.s. and the size of the pipe-arch, read $V_{FULL}=6.3$ f.p.s.
5. On the upper graph of chart 67, from $d/D=0.39$ and the relative velocity curve, read $V/V_{FULL}=2.21$.
6. Then $V_n=2.21\times6.3$ (from step 4)$=13.9$ f.p.s.

Example 20

Given: A long pipe-arch, 8 ft., 2 in., by 5 ft., 9 in., in cross section, with $n=0.025$, discharging 200 c.f.s. at a depth of flow of 4.0 ft. *Find:* S_f required to maintain the flow and the critical slope S_c for the given conditions.

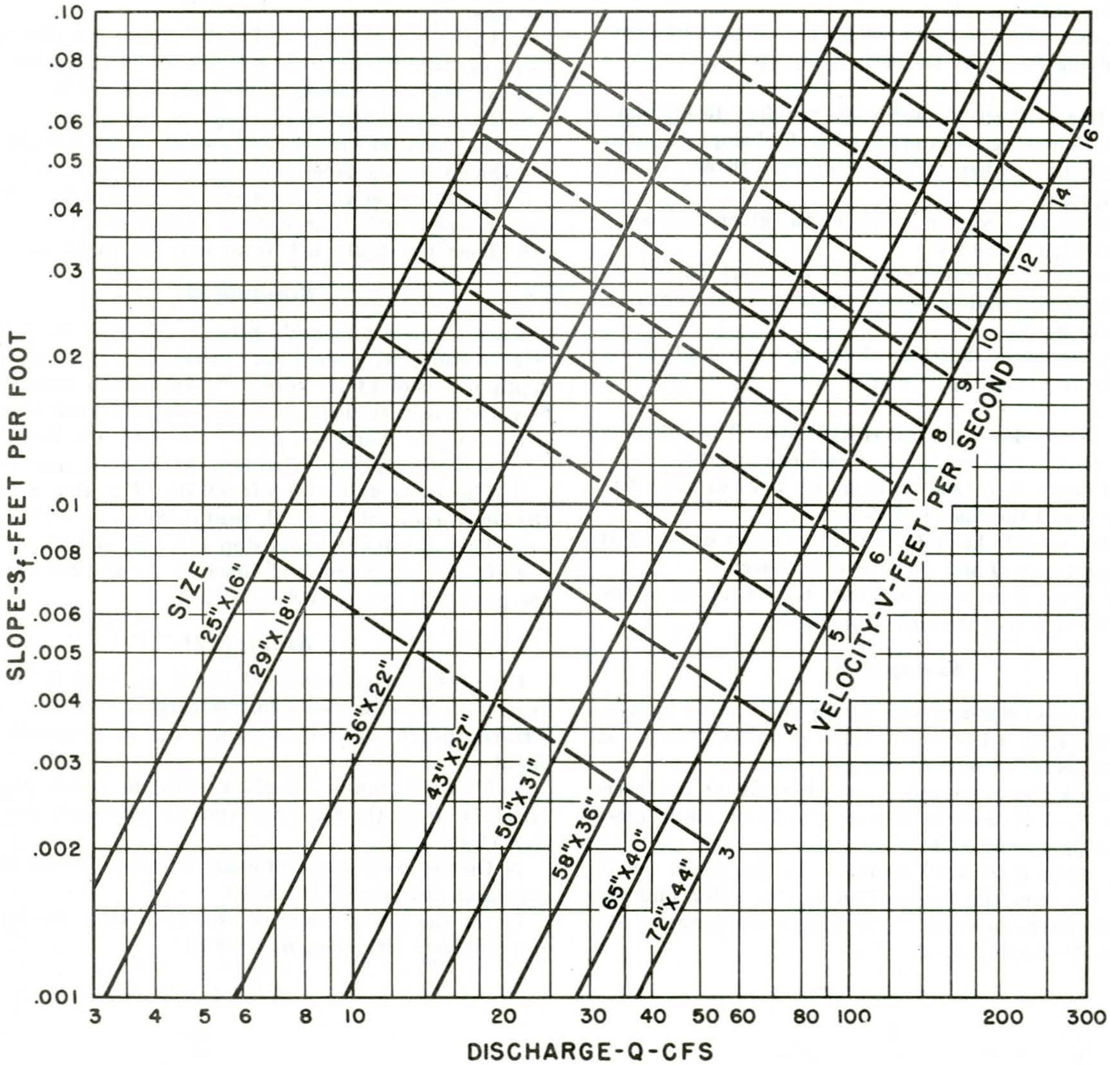
1. Group 3 charts are used. On chart 69, for $Q=200$ c.f.s. and the pipe-arch size (No. 6), read $S_{f\ FULL}=0.004$.
2. The ratio $d/D=4.0/5.75=0.70$. For this ratio, on the lower graph of chart 70, read $S_f/S_{f\ FULL}=1.25$.
3. Then $S_f=0.004$ (from step 1)$\times1.25=0.005$.
4. In the upper graph of chart 73, for $Q=200$ c.f.s. and the pipe-arch size, read $S_c=0.012$.

Example 21

Given: A long pipe-arch, 12 ft., 10 in., by 8 ft., 4 in., in cross section, with $n=0.025$, discharging 800 c.f.s. *Find:* Critical depth d_c, critical slope S_c, and specific head H_c at d_c.

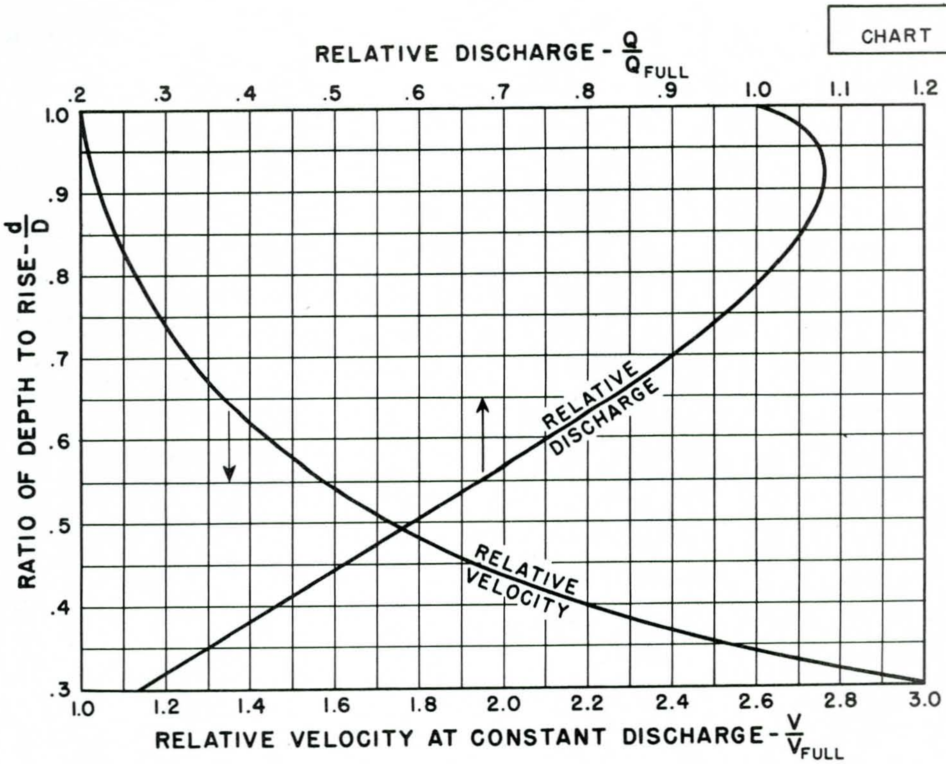
1. Group 3 charts are used. On the lower graph of chart 71, from $Q=800$ c.f.s. and the pipe-arch size, read $d_c=5.2$ ft.
2. On the lower graph of chart 73, from $Q=800$ and the pipe-arch size, read $S_c=0.0123$.
3. On the lower graph of chart 72, from $Q=800$ and the pipe-arch size, read $H_c=7.9$ ft.

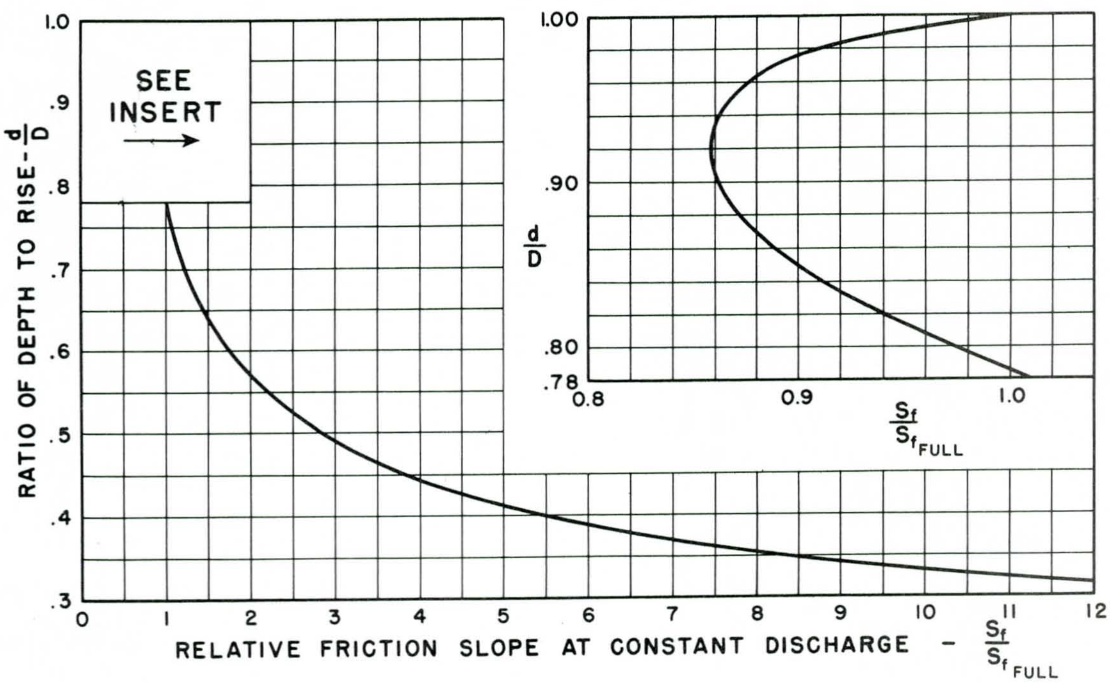
CHART 61



RIVETED C.M. PIPE-ARCH
FRICTION SLOPE FLOWING FULL
n = 0.024

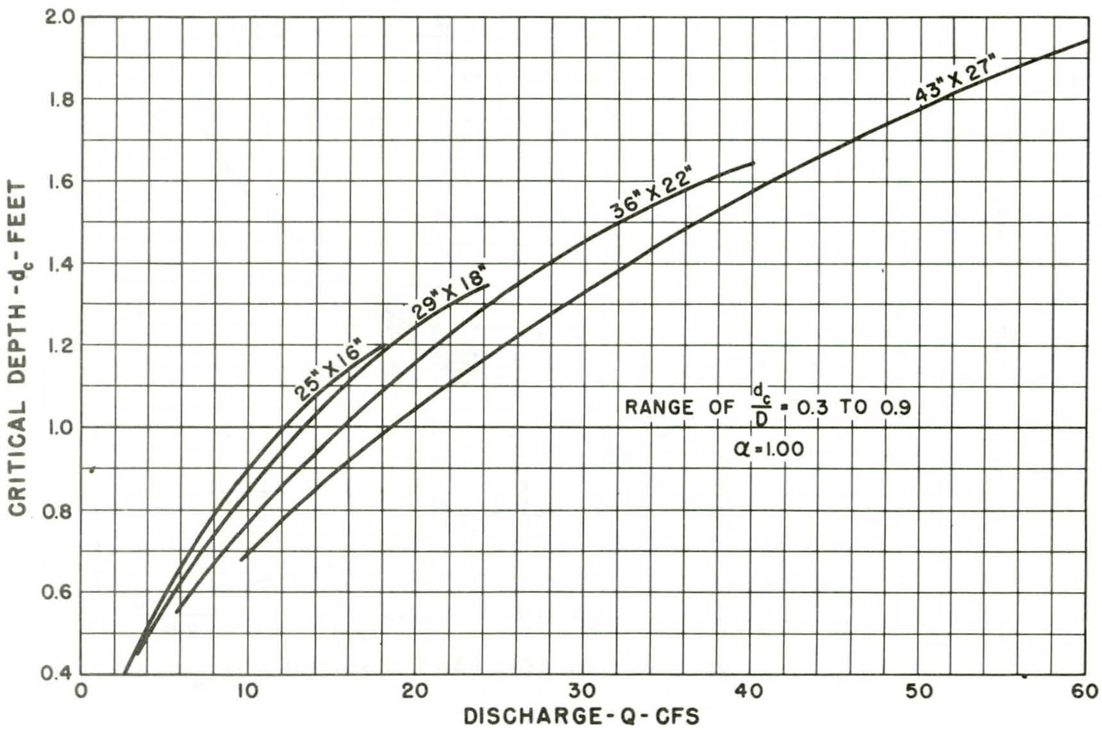
CHART 62

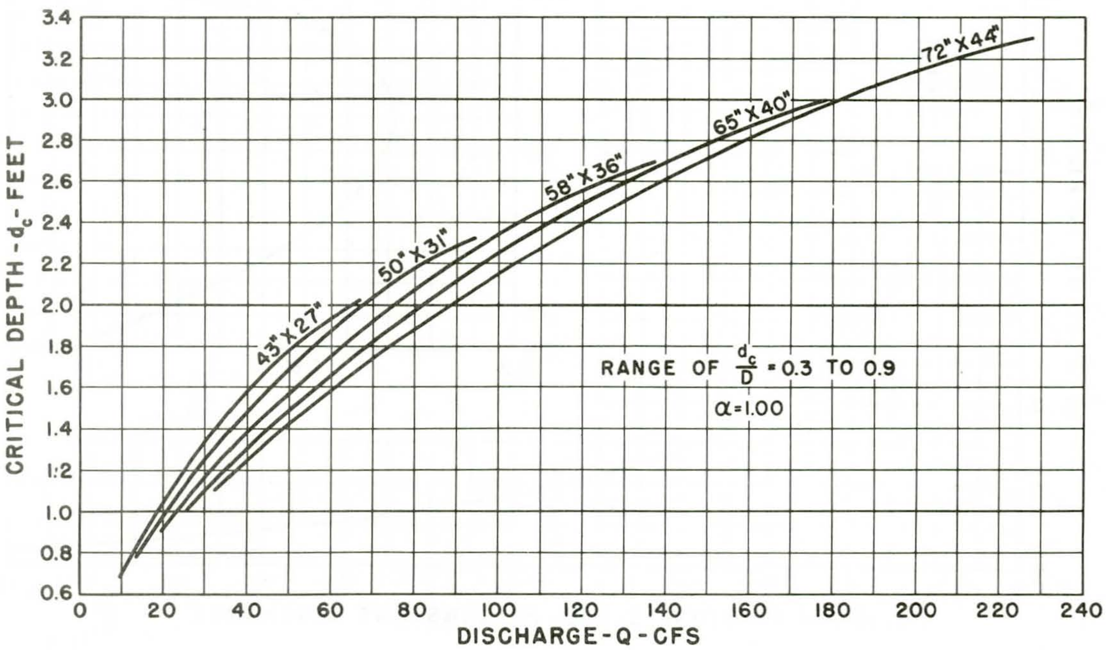




RIVETED C.M. PIPE-ARCH PART FULL FLOW

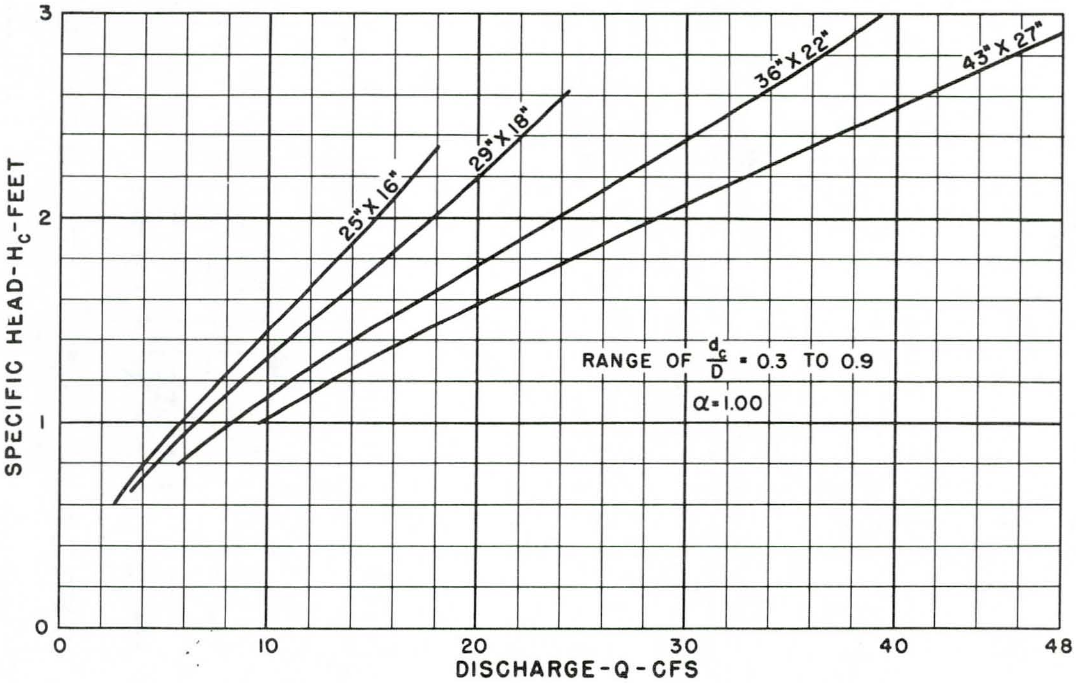
CHART 63

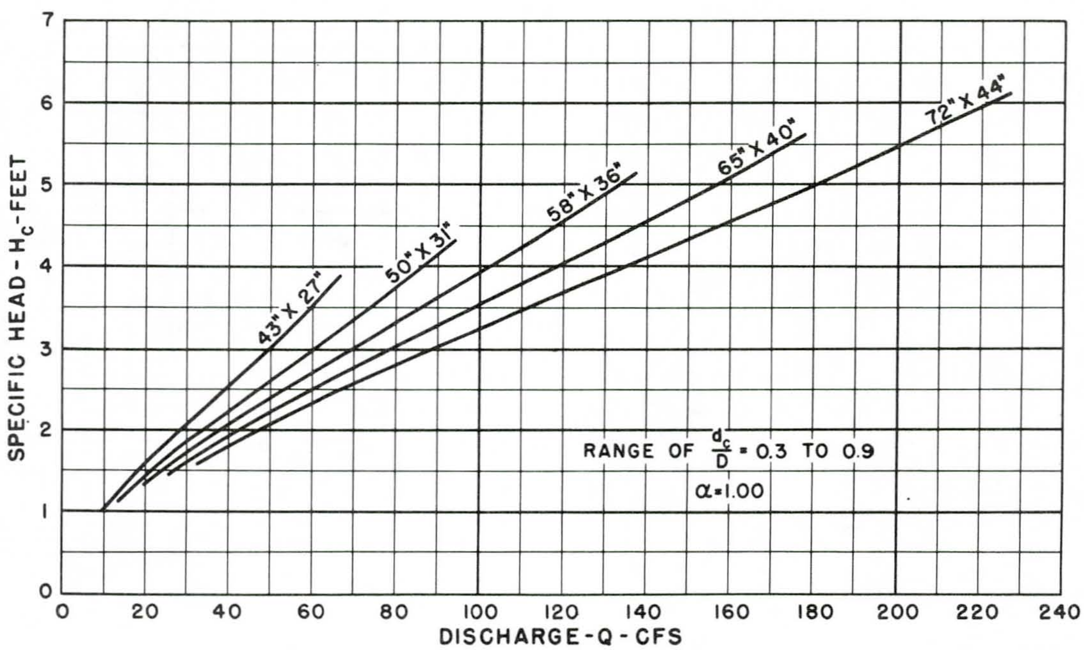




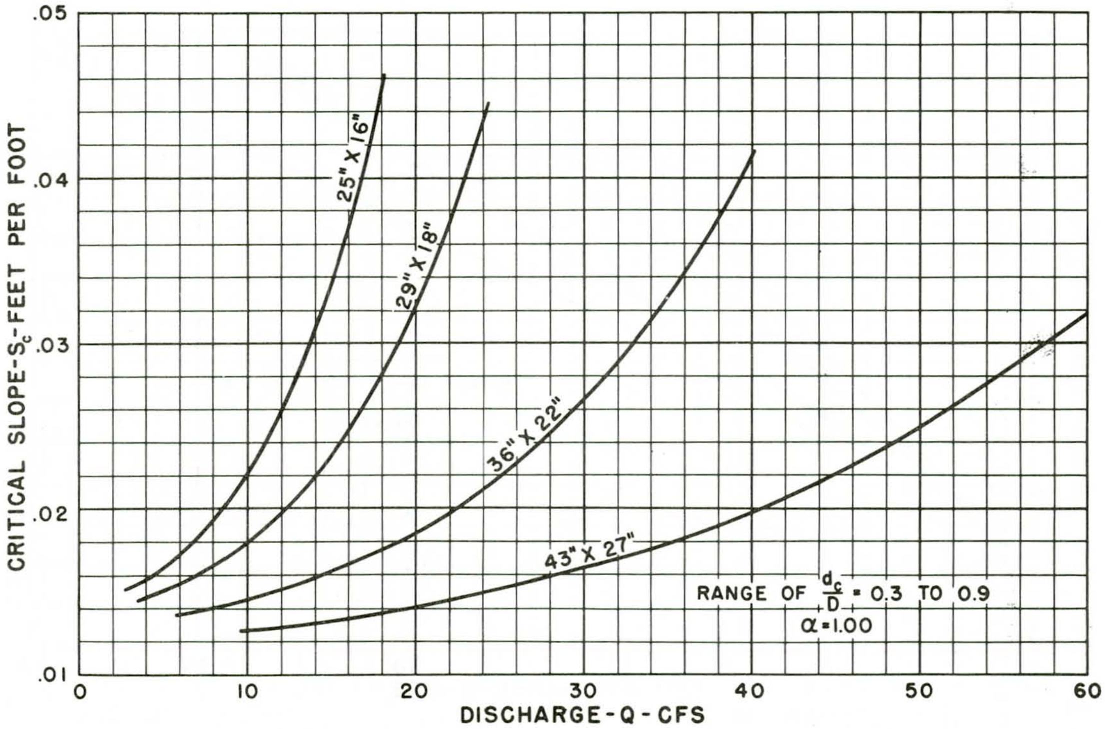
RIVETED C.M. PIPE-ARCH
CRITICAL DEPTH

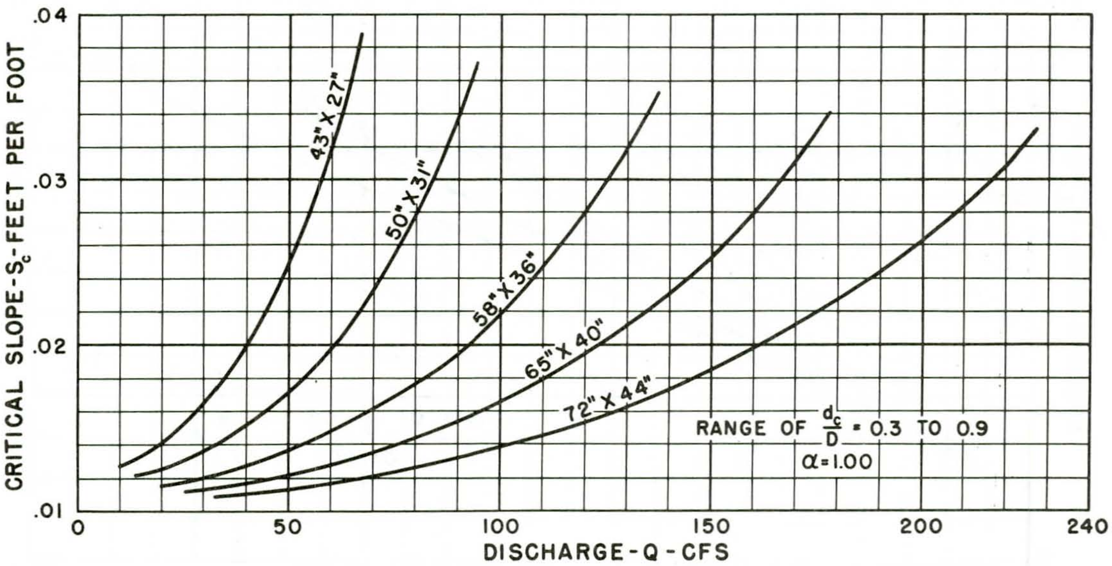
CHART 64





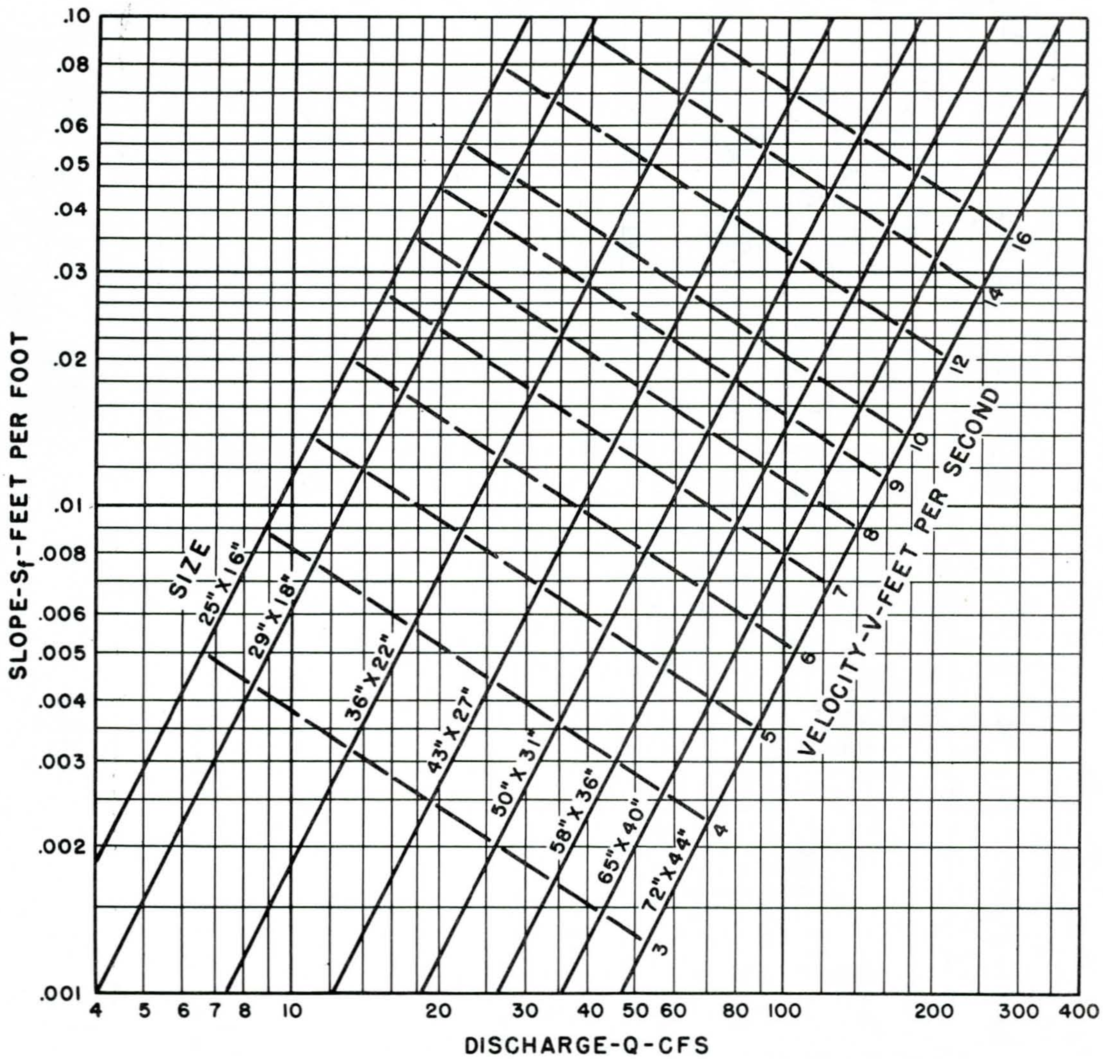
RIVETED C.M. PIPE-ARCH
SPECIFIC HEAD
AT CRITICAL DEPTH





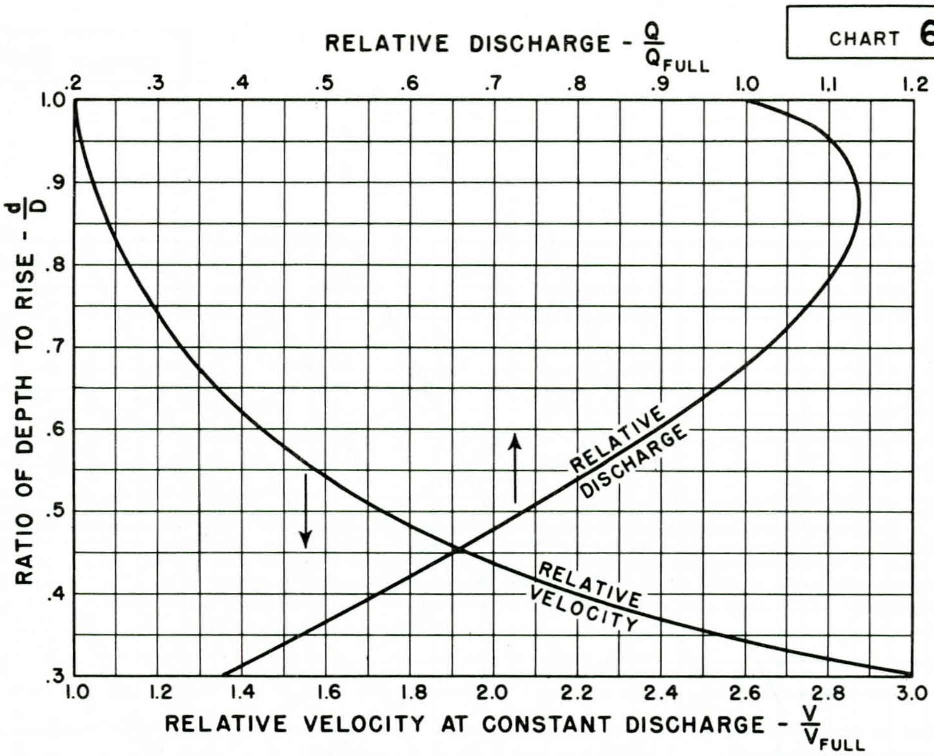
RIVETED C.M. PIPE-ARCH
CRITICAL SLOPE
n = 0.024

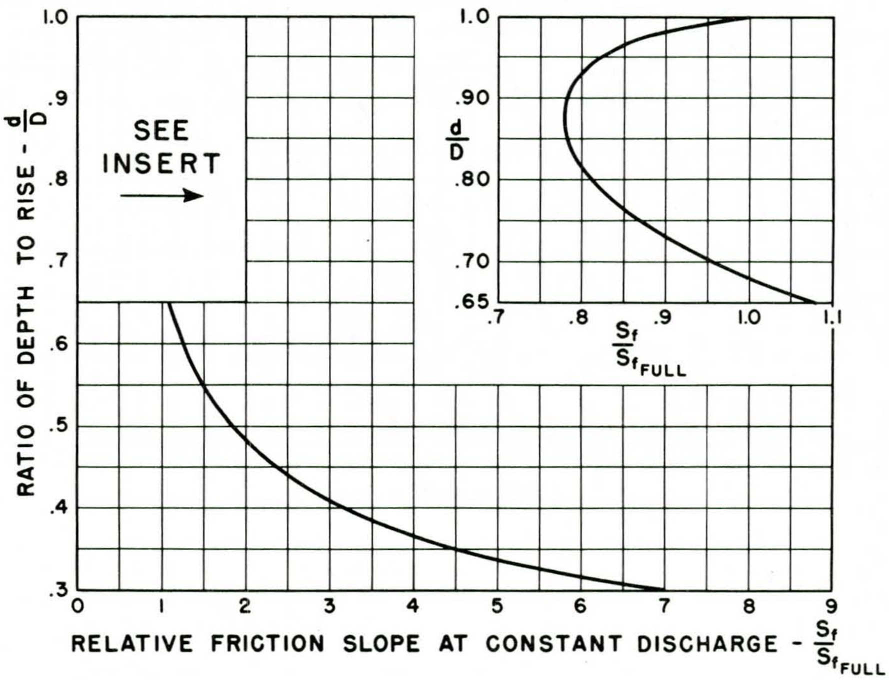
CHART 66



RIVETED C.M. PIPE-ARCH
40% PAVED INVERT
FRICTION SLOPE FLOWING FULL
n=0.019

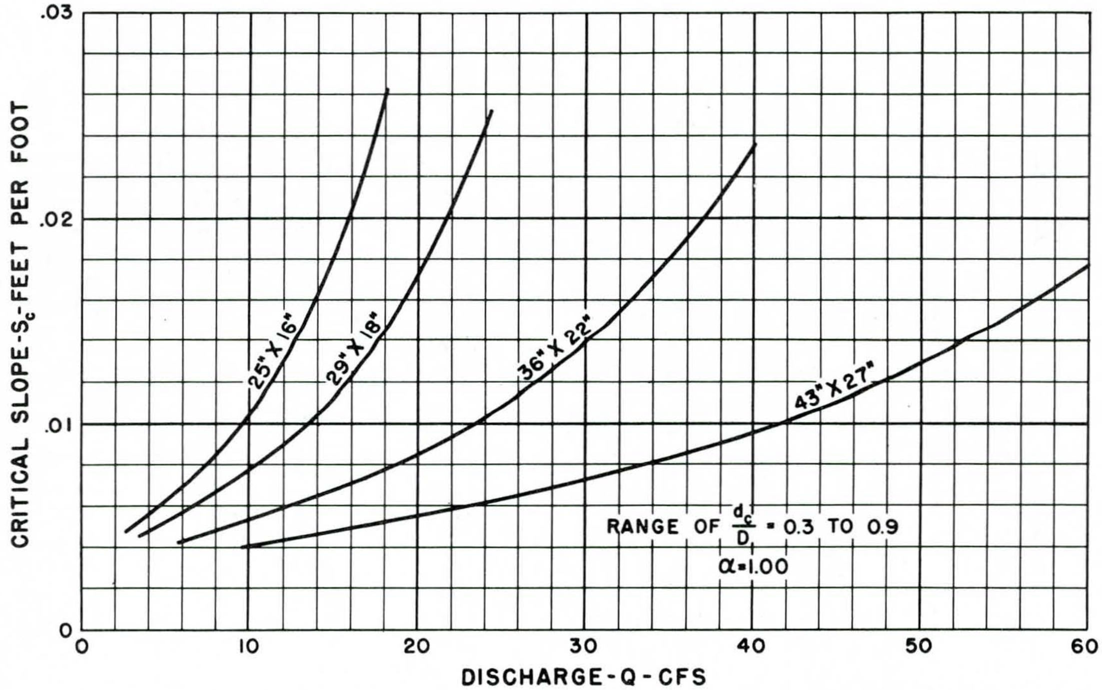
CHART 67

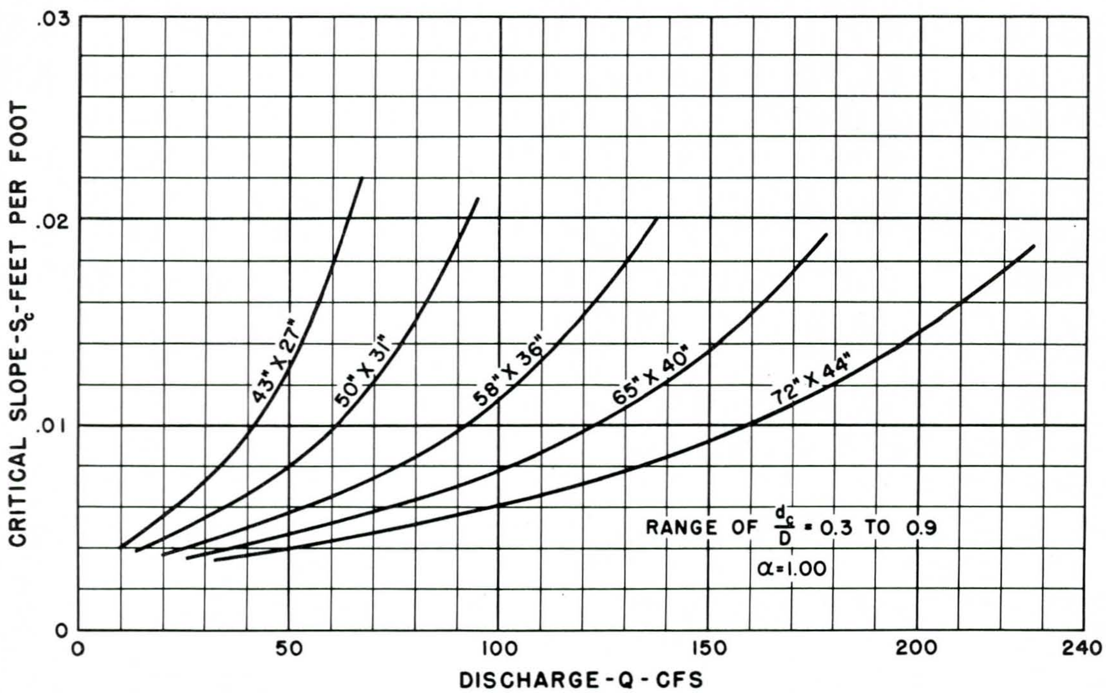




RIVETED C. M. PIPE-ARCH
40% PAVED INVERT
PART FULL FLOW
n = 0.012 TO 0.019

CHART 68





RIVETED C.M. PIPE-ARCH
40% PAVED INVERT
CRITICAL SLOPE
n = 0.012 TO 0.019

CHART 69

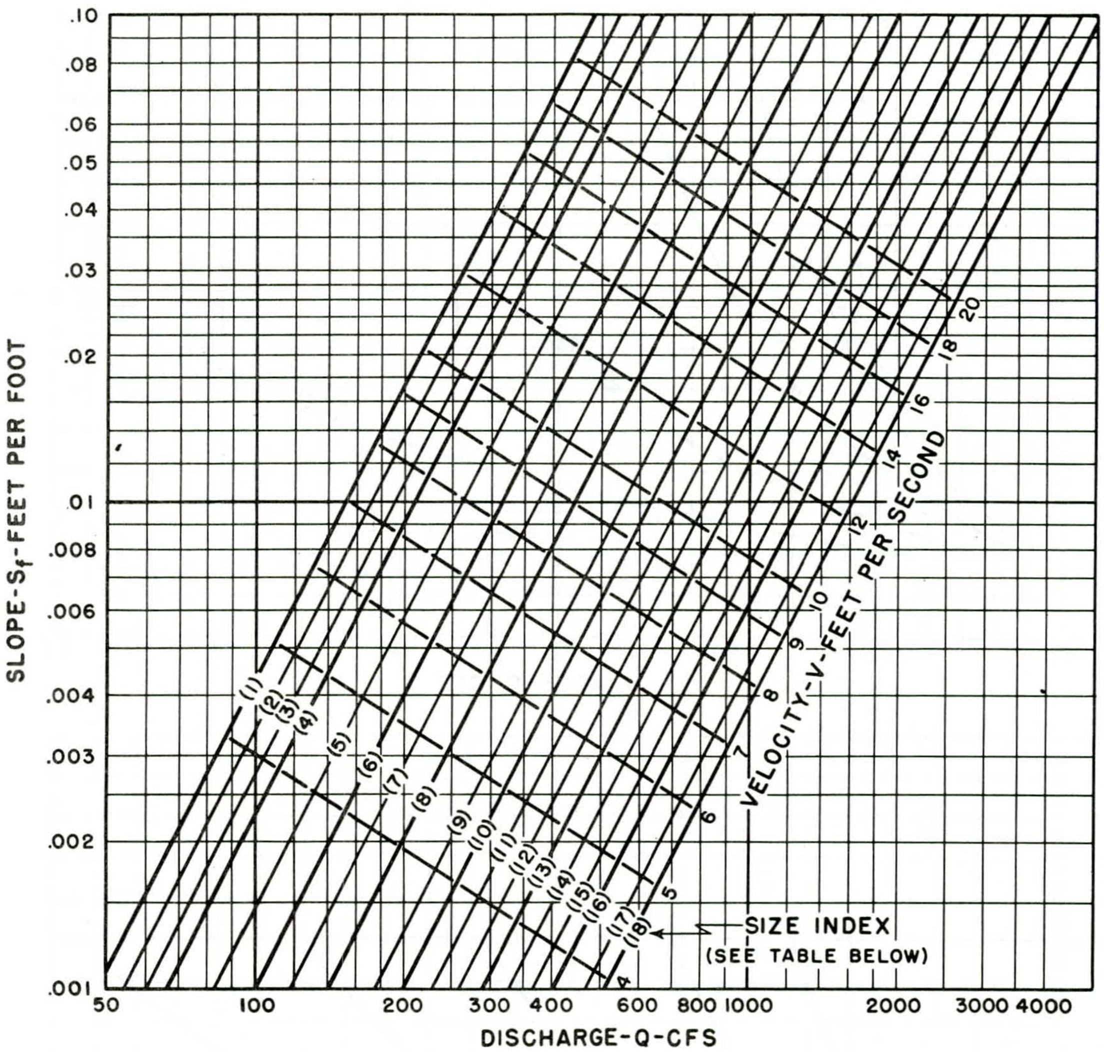
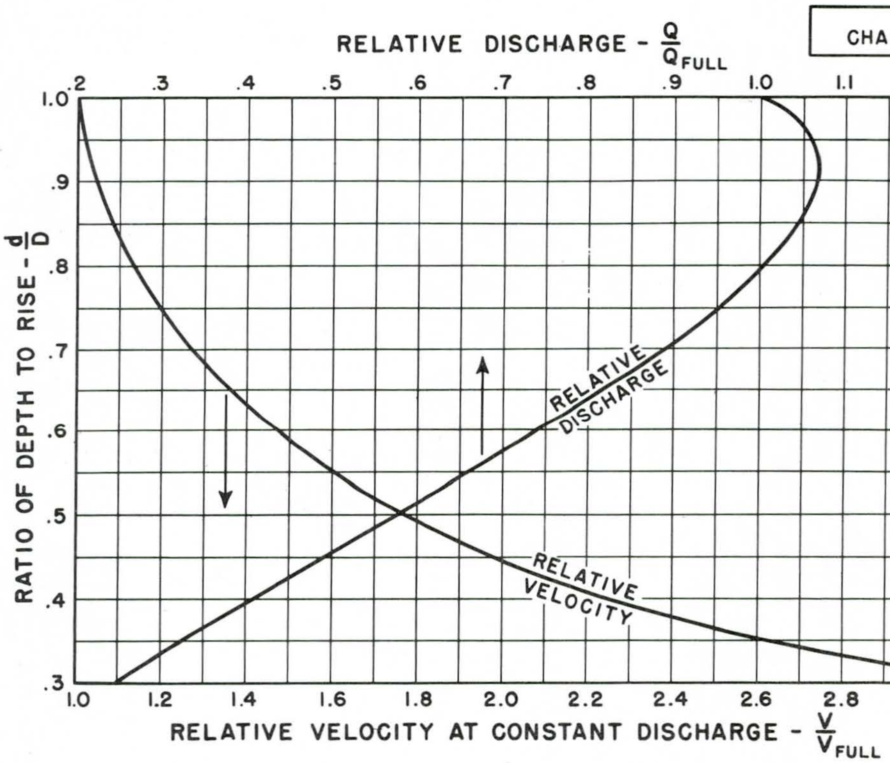
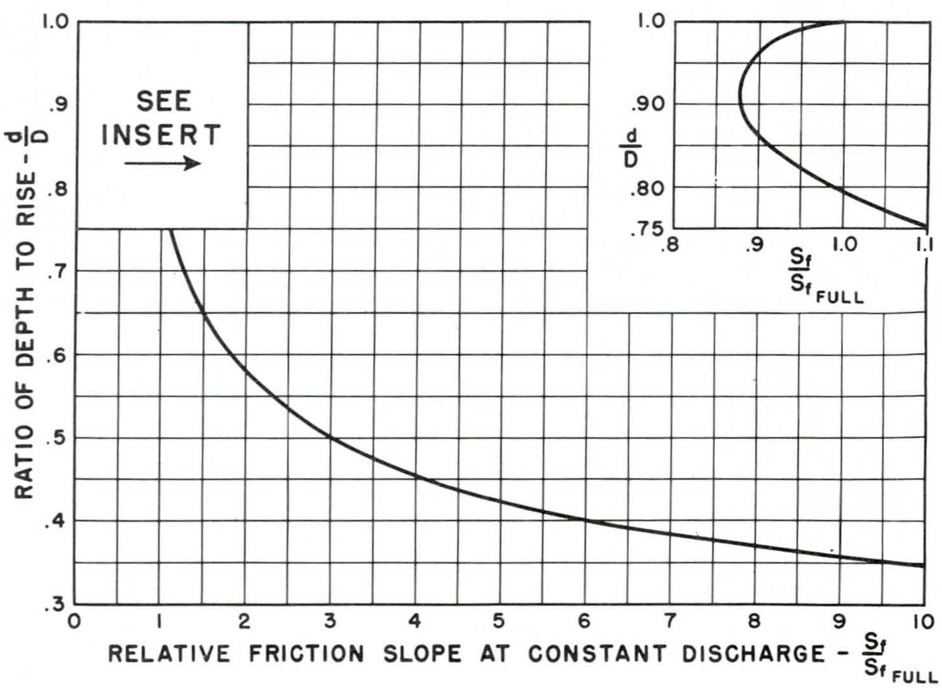


TABLE OF SIZES

(1) 6'- 1" X 4'- 7"	(7) 8'-10" X 6- 1"	(13) 12'-10" X 8'- 4"
(2) 6'- 4" X 4'- 9"	(8) 9'- 6" X 6'- 5"	(14) 13'-11" X 8'- 7"
(3) 6'- 9" X 4'-11"	(9) 10'- 8" X 6'-11"	(15) 14'- 3" X 8'- 11"
(4) 7'- 0" X 5'- 1"	(10) 11' - 5" X 7'- 3"	(16) 15'- 4" X 9'- 3"
(5) 7'- 8" X 5'- 5"	(11) 11' -10" X 7'- 7"	(17) 15'-10" X 9'-10"
(6) 8'- 2" X 5'- 9"	(12) 12'- 6" X 7'-11"	(18) 16'- 7" X 10- 1"

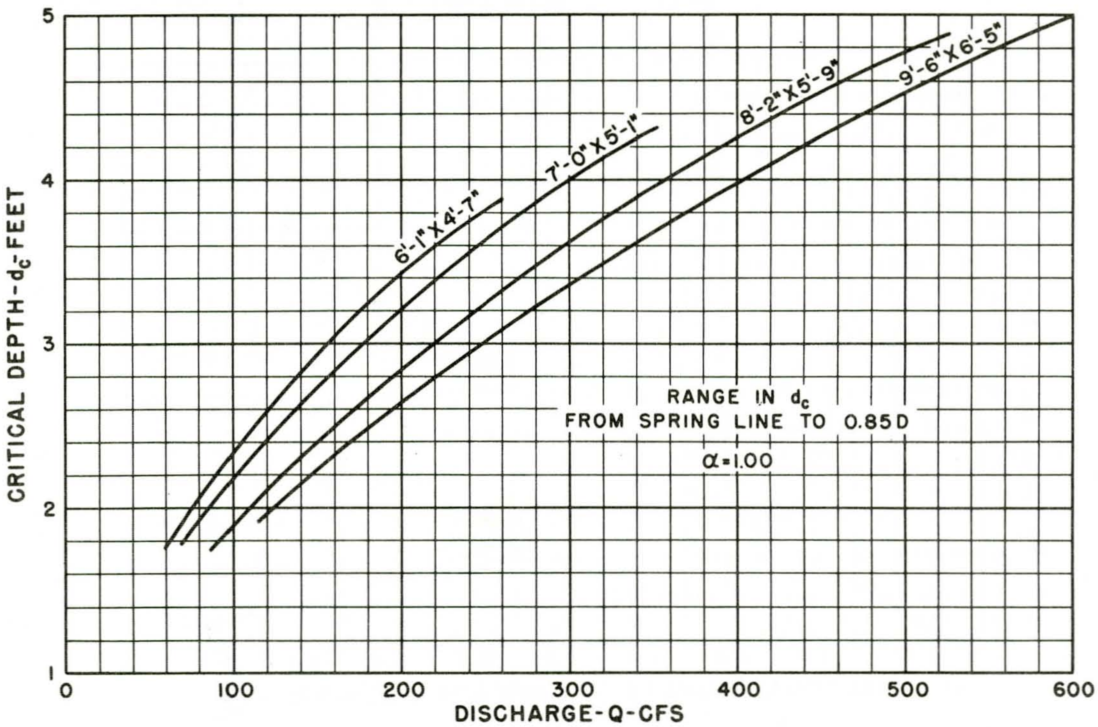
FIELD BOLTED C.M. PIPE-ARCH
FRICTION SLOPE FLOWING FULL
$n = 0.025$

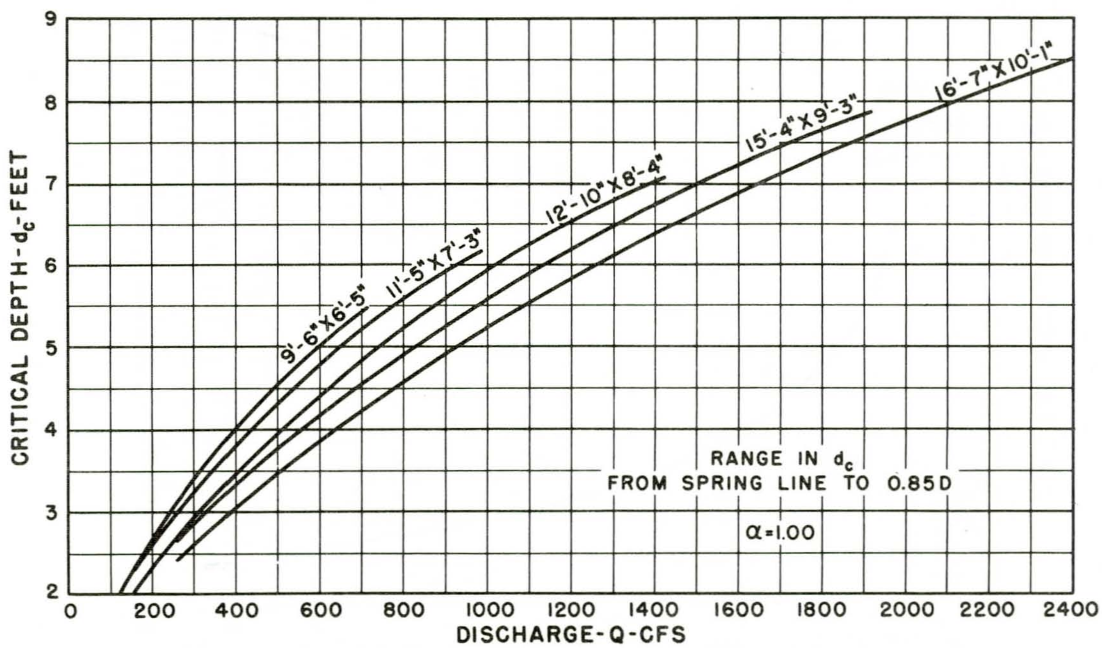




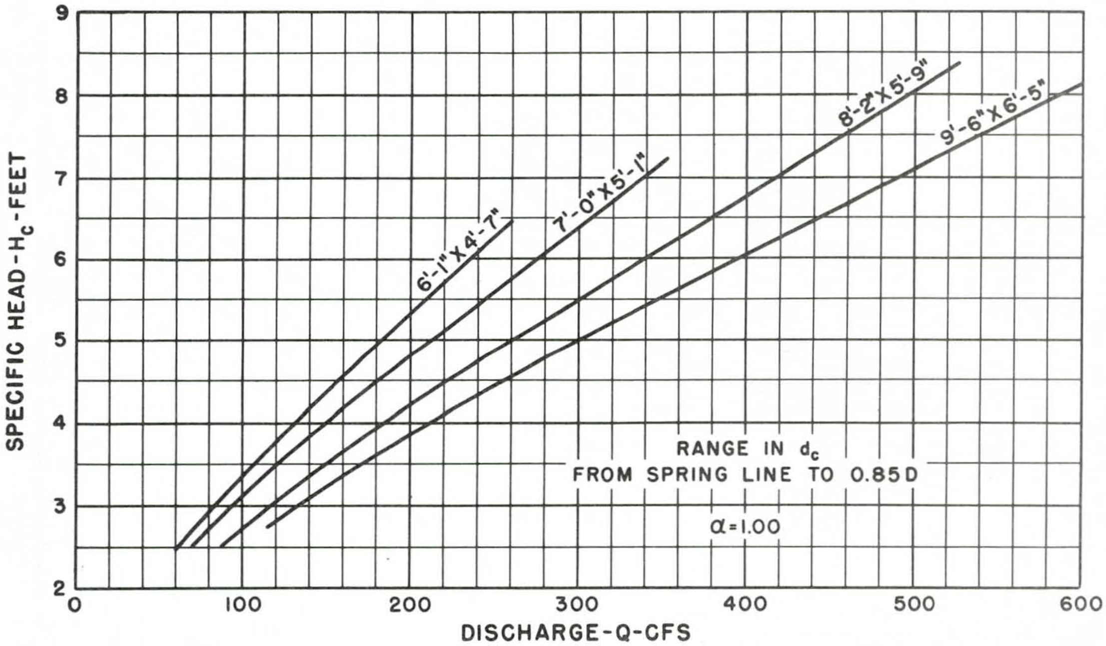
FIELD BOLTED C. M. PIPE-ARCH
PART FULL FLOW

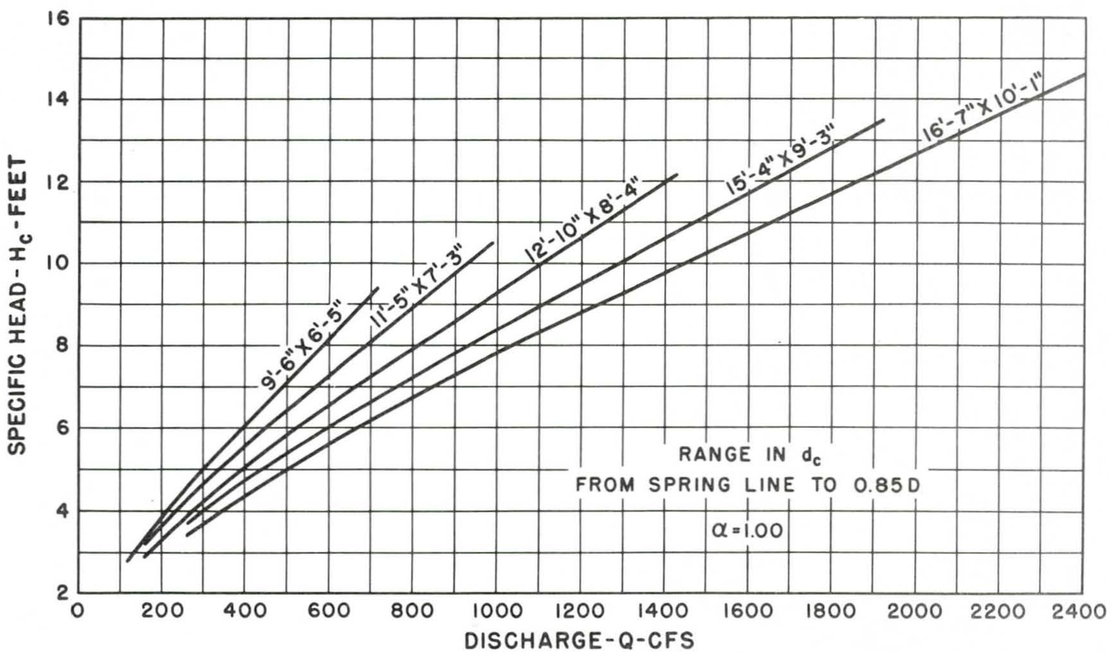
CHART 71



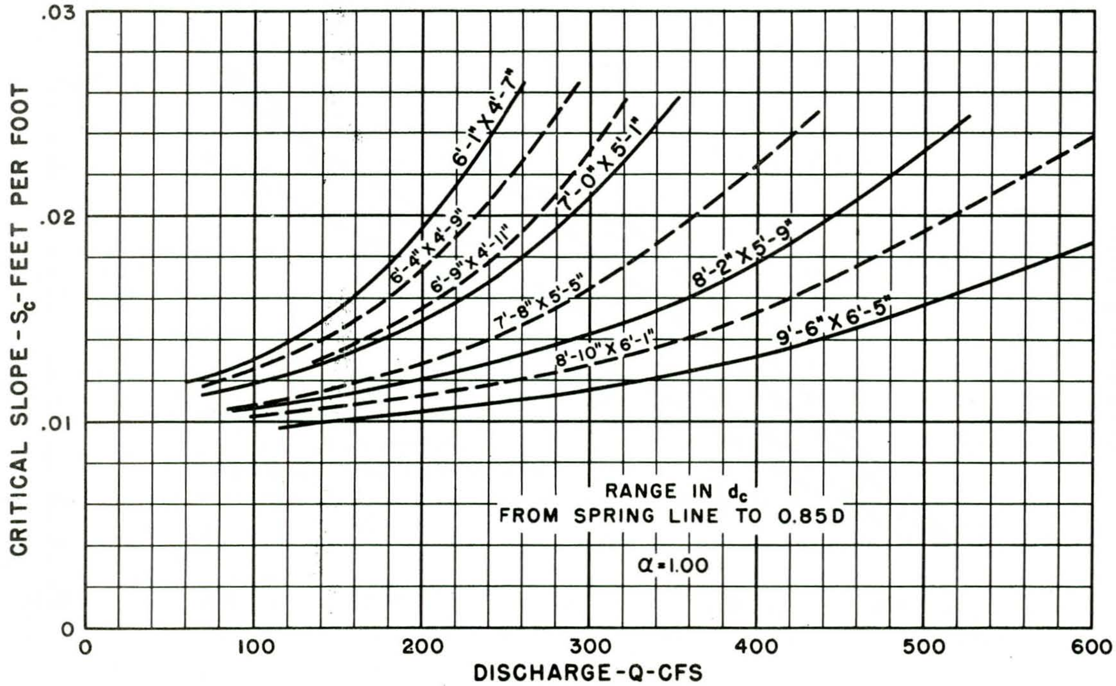


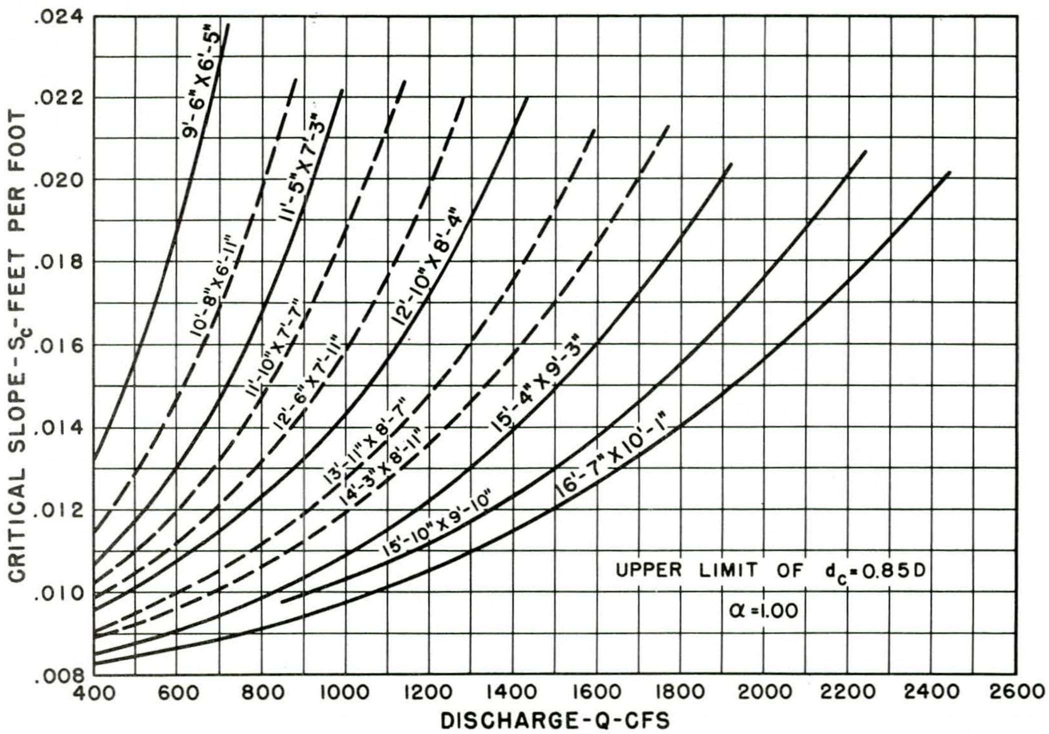
FIELD BOLTED C. M. PIPE - ARCH
CRITICAL DEPTH





FIELD BOLTED C.M. PIPE-ARCH
SPECIFIC HEAD
AT CRITICAL DEPTH





FIELD BOLTED C.M. PIPE-ARCH
CRITICAL SLOPE
$n = 0.025$

Chapter 7.—OVAL CONCRETE-PIPE CHANNELS

7.1 Description of charts. Charts 74–82 are designed for use in the solution of the Manning equation for flow in oval concrete-pipe channels which have sufficient length, on constant slope, to establish uniform flow at normal depth without backwater or pressure head. It is important to recognize that they are not suitable for use in connection with most types of culvert flow, since culvert flow is seldom uniform.

These charts are similar to charts 52–60, described in chapter 5, and to the pipe-arch charts, described in chapter 6. The group consists of chart 74, showing friction slope, discharge, and velocity for full flow; charts 75 and 76, showing ratios for computing part-full flow; and charts 77–82, used for computing critical flow.

Oval pipe can be laid with the long axis of its cross section either horizontal or vertical. Since the position of the long axis has no effect on flow when the pipe flows full, chart 74 can be used in either case. The position of the long axis does make a difference with part-full flow, however; thus separate charts are necessary for the part-full ratios, and chart 75 is provided for horizontal long axis and chart 76 for vertical long axis. Separate charts are similarly necessary for critical flow, and charts 77–79 are provided for horizontal long axis and charts 80–82 for vertical long axis.

It should be noted that a considerable range of pipe sizes are listed at the bottom of chart 74, and all of these sizes are shown on the pertinent charts except Nos. 77 and 80. On these latter charts, interpolations can be made, when necessary; reading, for a particular size, between the curves for the next larger and next smaller sizes. It should also be noted that dimensions are shown appropriately on charts 77–82 according to whether the long axis is horizontal or vertical; for example, the pipe shown as 23 by 14 in. on chart 77 is shown as 14 by 23 in. on the corresponding chart 80.

7.2 Instructions for use of charts 74–82. The use of charts 74–82 requires, first, finding the friction slope for the given discharge in a pipe flowing full, using chart 74. Then the ratio graphs of chart 75 or 76 are used to find solutions for discharge Q, depth d, velocity V, and friction slope S_f.

Critical depth d_c, specific head at critical depth H_c, and critical slope S_c are determined from charts 77–79 or 80–82.

More detailed instructions for the use of the charts follow.

7.2–1 Use of charts to find discharge. The following steps are used to find discharge, when depth of flow and slope of pipe are known (see example 22).

First find full-flow discharge Q_{FULL} corresponding to the slope of the pipe, using chart 74.

Next compute the ratio of the depth of flow to the rise of the pipe, d/D, and on chart 75 or 76 read the corresponding Q/Q_{FULL}, using the relative discharge curve in the upper graph.

Finally, compute the discharge at the given depth by multiplying the full-flow discharge (from the first step) by the ratio Q/Q_{FULL} (from the second step).

7.2–2 Use of charts to find depth of uniform flow. The following steps are used to find depth of uniform flow, when discharge and slope are known (see example 23).

First find Q_{FULL} corresponding to the slope of the pipe, using chart 74.

Next compute the ratio Q/Q_{FULL} and on chart 75 or 76, using the ratio and the relative discharge curve in the upper graph, find the corresponding d/D.

Finally, compute depth of flow by multiplying the pipe rise D by d/D (from the second step). D and d must be in the same units.

7.2–3 Use of charts to find velocity of flow. The following steps are used to find velocity of flow, when discharge and slope are known (see example 23).

First find V_{FULL} corresponding to the given discharge rate, using chart 74.

If depth of flow is unknown, determine it according to the instructions in section 7.2–2.

Next compute the ratio d/D and, using the relative velocity curve in the upper graph of chart 75 or 76, find the corresponding V/V_{FULL}.

Finally, compute the mean velocity V of part-full flow by multiplying V_{FULL} by the ratio V/V_{FULL}.

7.2–4 Use of charts to find slope required to maintain flow. The following steps are used to find slope required to maintain flow, when discharge and depth are known (see example 24).

First find $S_{f\ FULL}$ corresponding to the given discharge, using chart 74.

Next compute the ratio d/D, and in the lower graph of chart 75 or 76 read the corresponding relative friction slope $S_f/S_{f\ FULL}$.

Finally, compute the friction slope S_f by multiplying $S_{f\ FULL}$ by the ratio $S_f/S_{f\ FULL}$.

7.2–5 Use of charts to find critical flow. The following steps are used to find critical flow (see example 25).

Critical depth d_c for a given discharge is read on chart 77 or 80, from the intersection of Q and size of pipe.

Minimum specific head H_c for a given discharge is read on chart 78 or 81, from the intersection of Q and the size of pipe.

Example 22

Given: A long oval pipe, 76 in. by 48 in. in cross section, long axis horizontal, with $n=0.011$, on a 1.0-percent slope ($S=0.01$), flowing at a depth of 3.0 ft. *Find:* Discharge.

1. On chart 74, find the intersection for $S=0.01$ and pipe size (No. 11); move vertically down and read $Q_{FULL}=320$ c.f.s.

2. The ratio $d/D=3.0/4.0=0.75$. In the upper graph of chart 75, find the intersection for this ratio and the relative discharge curve; move vertically up and read $Q/Q_{FULL}=0.94$.

3. Then $Q=320$ (from step 1)$\times 0.94$ (from step 2)$=$ 300 c.f.s.

Example 23

Given: A long, oval concrete pipe, 49 in. by 32 in. in cross section, with $n=0.011$, on a 0.6-percent slope ($S=0.006$), discharging 60 c.f.s. *Find:* Depth and velocity, for long axis either horizontal or vertical.

1. On chart 74, for $S=0.006$ and the pipe size (No. 7), read $Q_{FULL}=80$ c.f.s.

2. Compute $Q/Q_{FULL}=60/80=0.75$.

3. Again on chart 74, using $Q=60$ and the pipe size, read $V_{FULL}=$ 6.8 f.p.s.

4. For long axis horizontal:

4a. Using chart 75, from $Q/Q_{FULL}=0.75$ (on the top scale) and the relative discharge curve, find ratio $d/D=0.64$.

4b. With the long axis horizontal, $D=32$ in.$=32/12$ ft. Then $d_n=0.64\times 32/12=1.7$ ft.

4c. Again using chart 75, from $d/D=0.64$ and the relative velocity curve, find $V/V_{FULL}=1.50$ (on the bottom scale).

4d. Then $V_n=1.50\times 6.8$ (from step 3)$=10.2$ f.p.s.

5. For long axis vertical:

5a. Using chart 76, from $Q/Q_{FULL}=0.75$ and the relative discharge curve, find ratio $d/D=0.66$.

5b. With the long axis vertical, $D=49$ in.$=49/12$ ft. Then $d_n=0.66\times 49/12=2.7$ ft.

5c. Again using chart 76, from $d/D=0.66$ and the relative velocity curve, find $V/V_{FULL}=1.43$.

5d. Then $V_n=1.43\times 6.8$ (from step 3)$=9.7$ f.p.s.

Example 24

Given: A long oval concrete pipe, 38 in. by 24 in. in cross section, long axis horizontal, with $n=0.011$, discharging 6C c.f.s. at a depth of flow of 1.5 ft. *Find:* Slope S_f required to maintain flow.

1. On chart 74, from $Q=60$ c.f.s. and the pipe size (No. 4), read $S_{f\ FULL}=0.015$.

2. Since the long axis is horizontal, $D=24$ in.$=2.0$ ft. The ratio $d/D=1.5/2.0=0.75$.

3. For $d/D=0.75$, on the lower graph of chart 75, read the relative friction slope $S_f/S_{f\ FULL}=1.15$.

4. Then $S_f=0.015\times 1.15=0.017$.

Example 25

Given: A long oval concrete pipe, 49 in. by 32 in. in cross section, with $n=0.011$, on a 0.6-percent slope ($S=0.006$), discharging 60 c.f.s. (the same conditions as in example 23). *Find:* d_c, S_c, and H_c at d_c, for long axis either horizontal or vertical.

1. For long axis horizontal:

1a. On chart 77, from $Q=60$ and the pipe size (interpolated), read $d_c=2.05$.

1b. On chart 78, from $Q=60$ and the pipe size, read $H_c=3.05$ ft.

1c. On chart 79, from $Q=60$ and the pipe size, read $S_c=0.0035$.

2. For long axis vertical:

2a. On chart 80, from $Q=60$ and the pipe size (interpolated), read $d_c=2.9$.

2b. On chart 81, from $Q=60$ and the pipe size, read $H_c=4.2$ ft.

2c. On chart 82, from $Q=60$ and the pipe size, read $S_c=0.0052$.

CHART 74

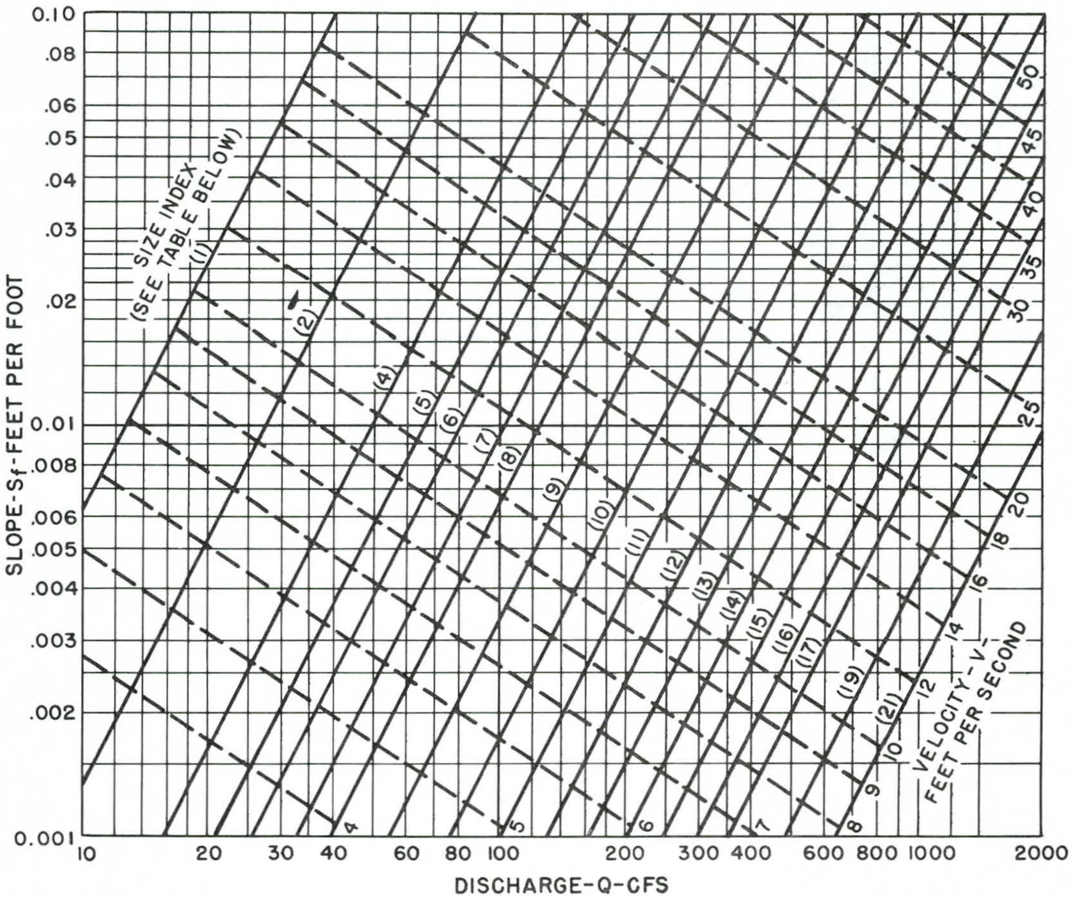
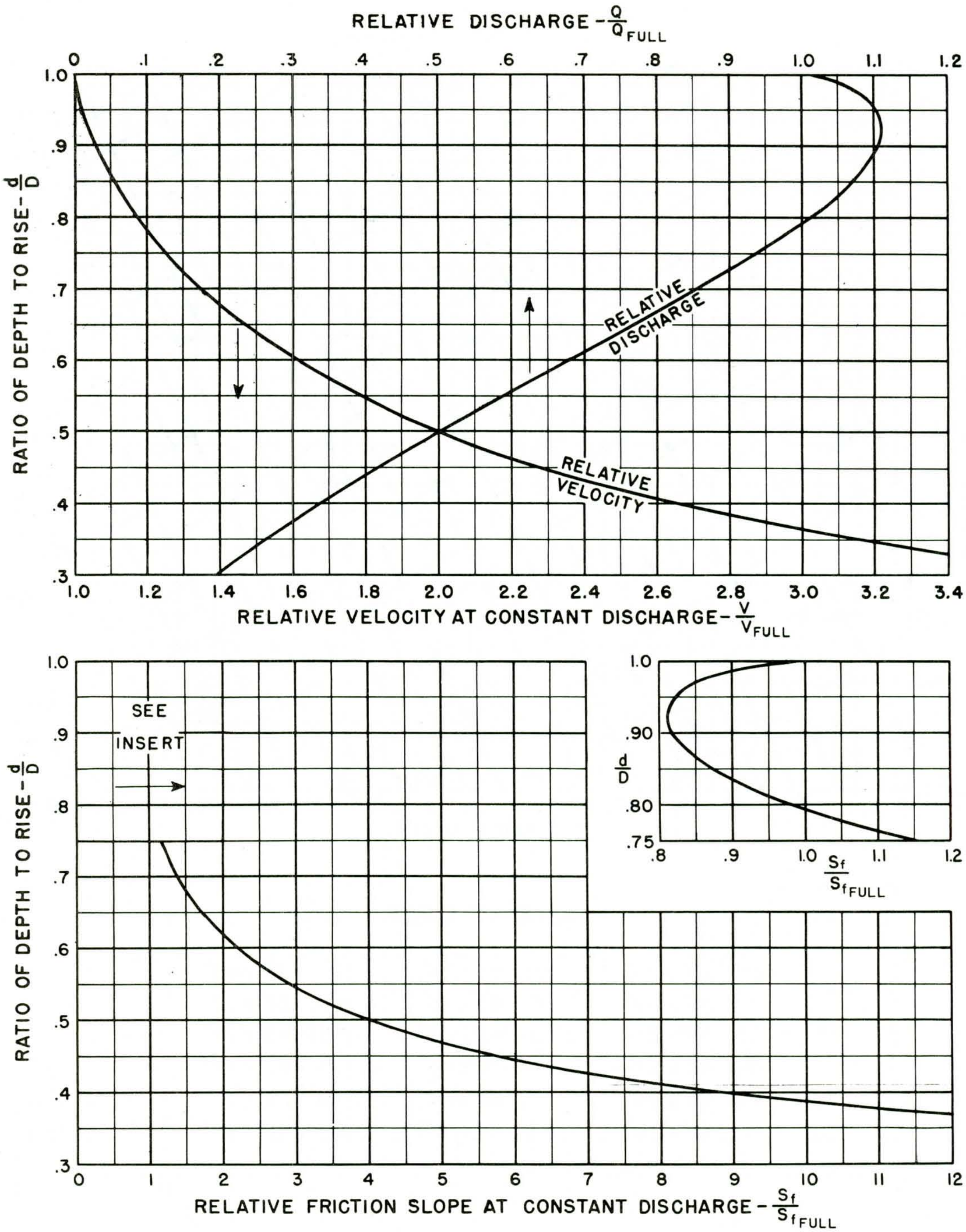


TABLE OF SIZES

(1)	23" x 14"	(8)	53" x 34"	(14)	98" x 63"
(2)	30" x 19"	(9)	60" x 38"	(15)	106" x 68"
(4)	38" x 24"	(10)	68" x 43"	(16)	113" x 72"
(5)	42" x 27"	(11)	76" x 48"	(17)	121" x 77"
(6)	45" x 29"	(12)	83" x 53"	(19)	136" x 87"
(7)	49" x 32"	(13)	91" x 58"	(21)	151" x 97"

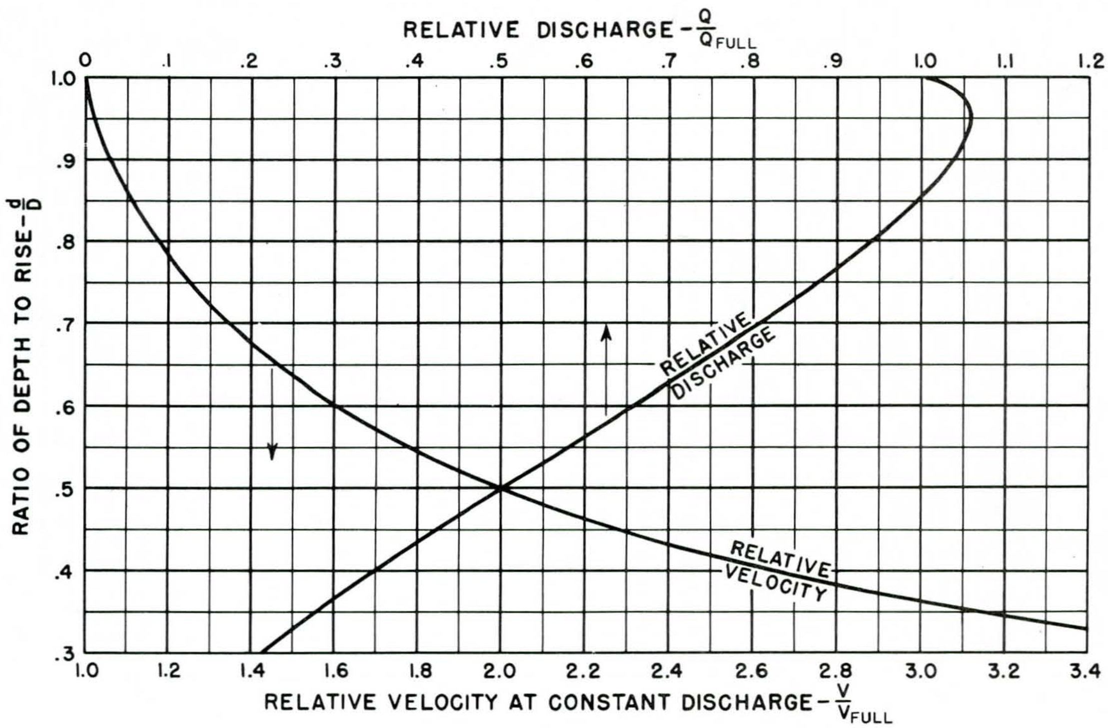
OVAL CONCRETE PIPE
FRICTION SLOPE FLOWING FULL
n = 0. 011

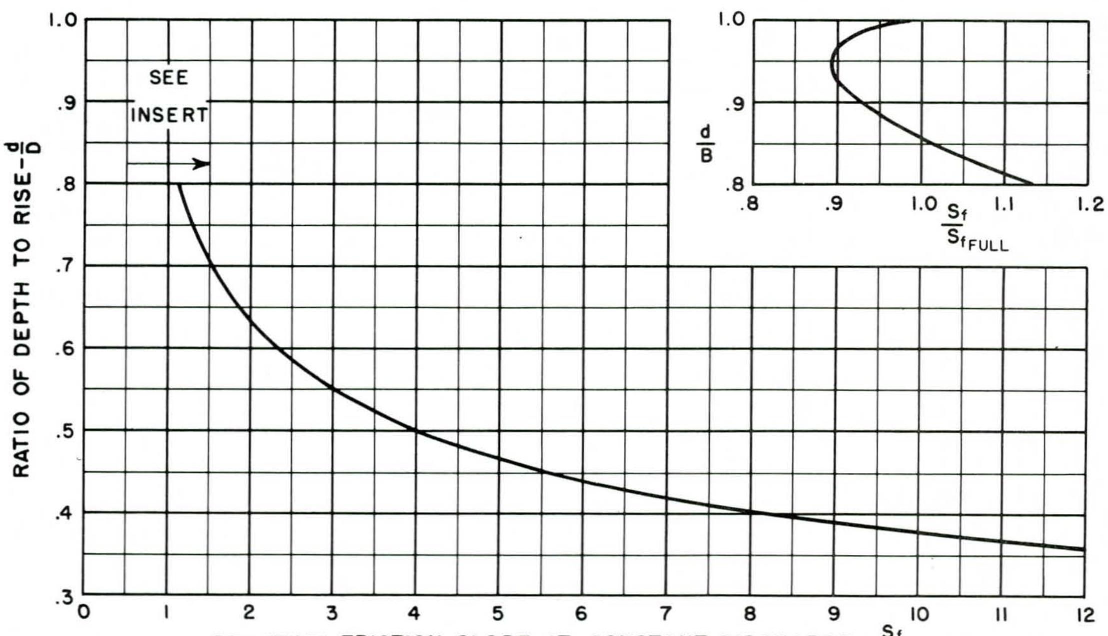
CHART 75



OVAL CONCRETE PIPE
LONG AXIS HORIZONTAL
PART FULL FLOW

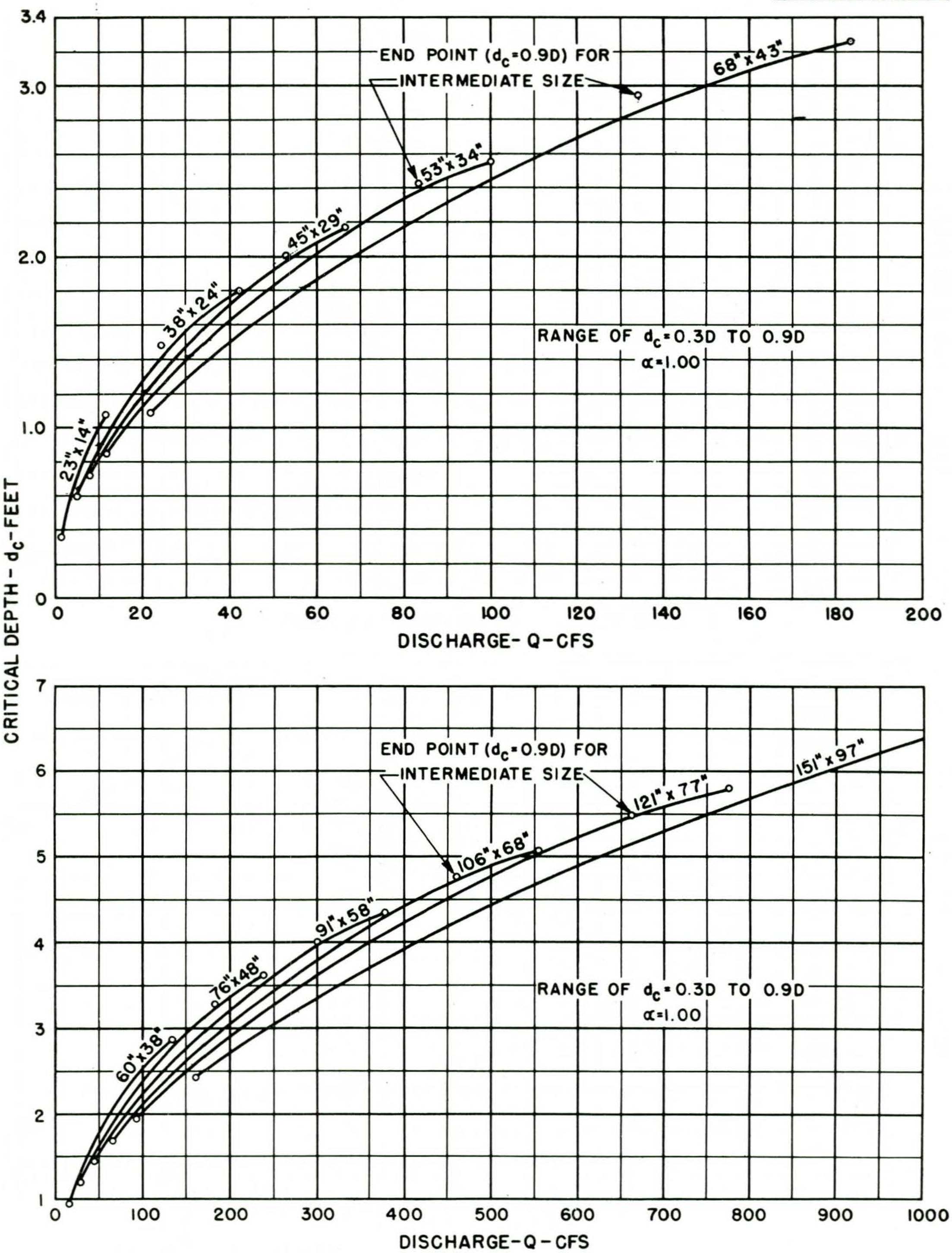
CHART 76





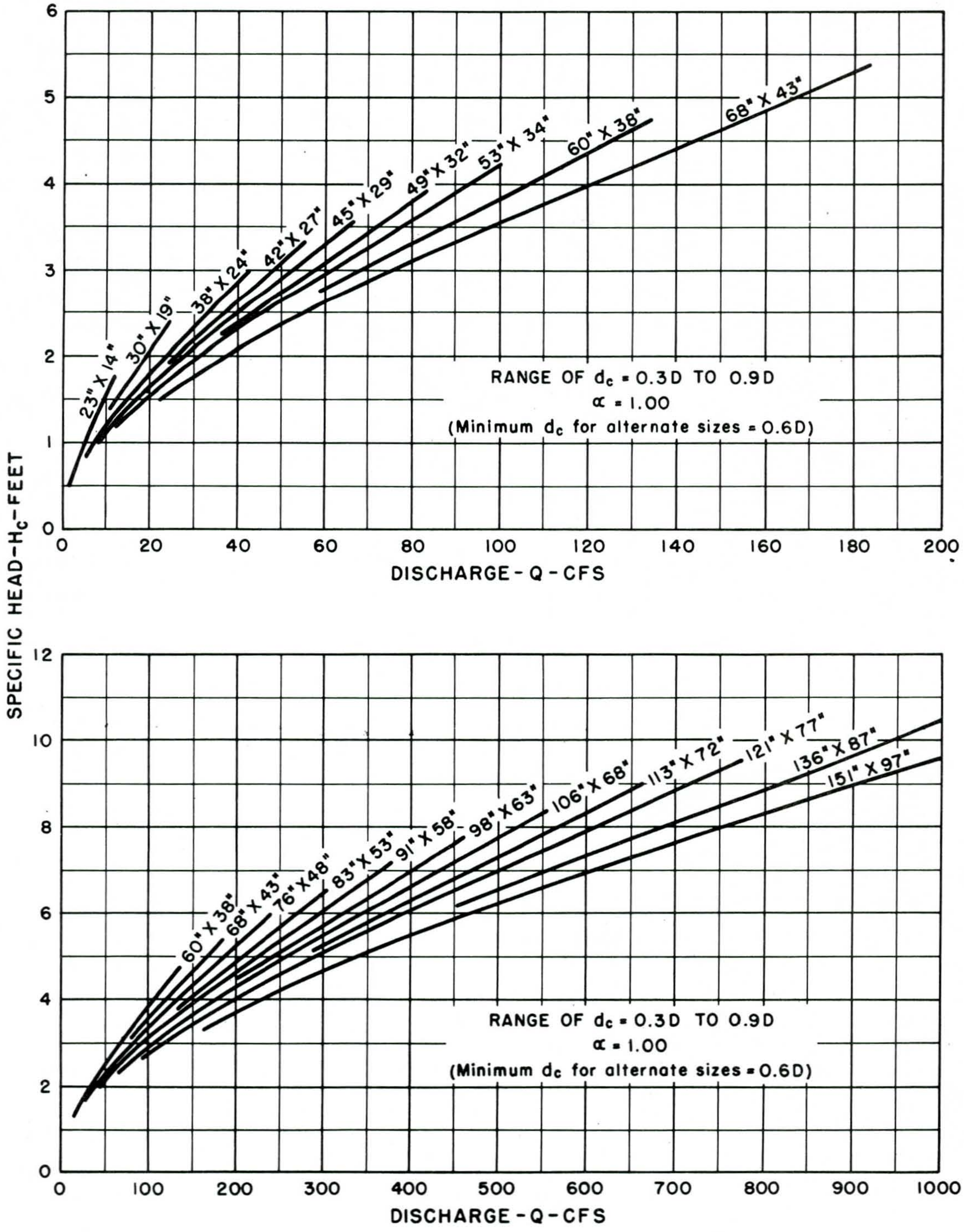
OVAL CONCRETE PIPE
LONG AXIS VERTICAL
PART FULL FLOW

CHART 77



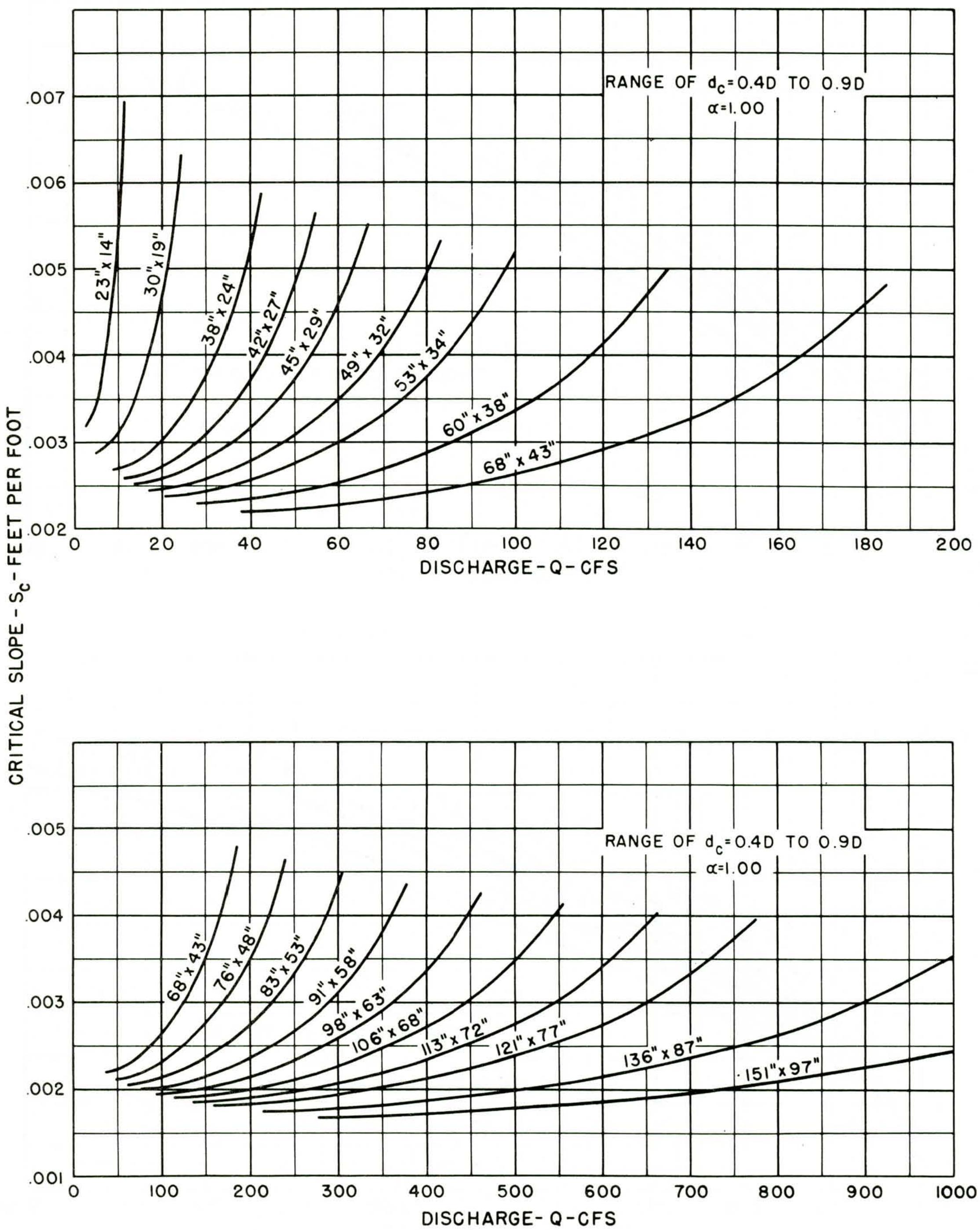
OVAL CONCRETE PIPE
LONG AXIS HORIZONTAL
CRITICAL DEPTH

CHART 78



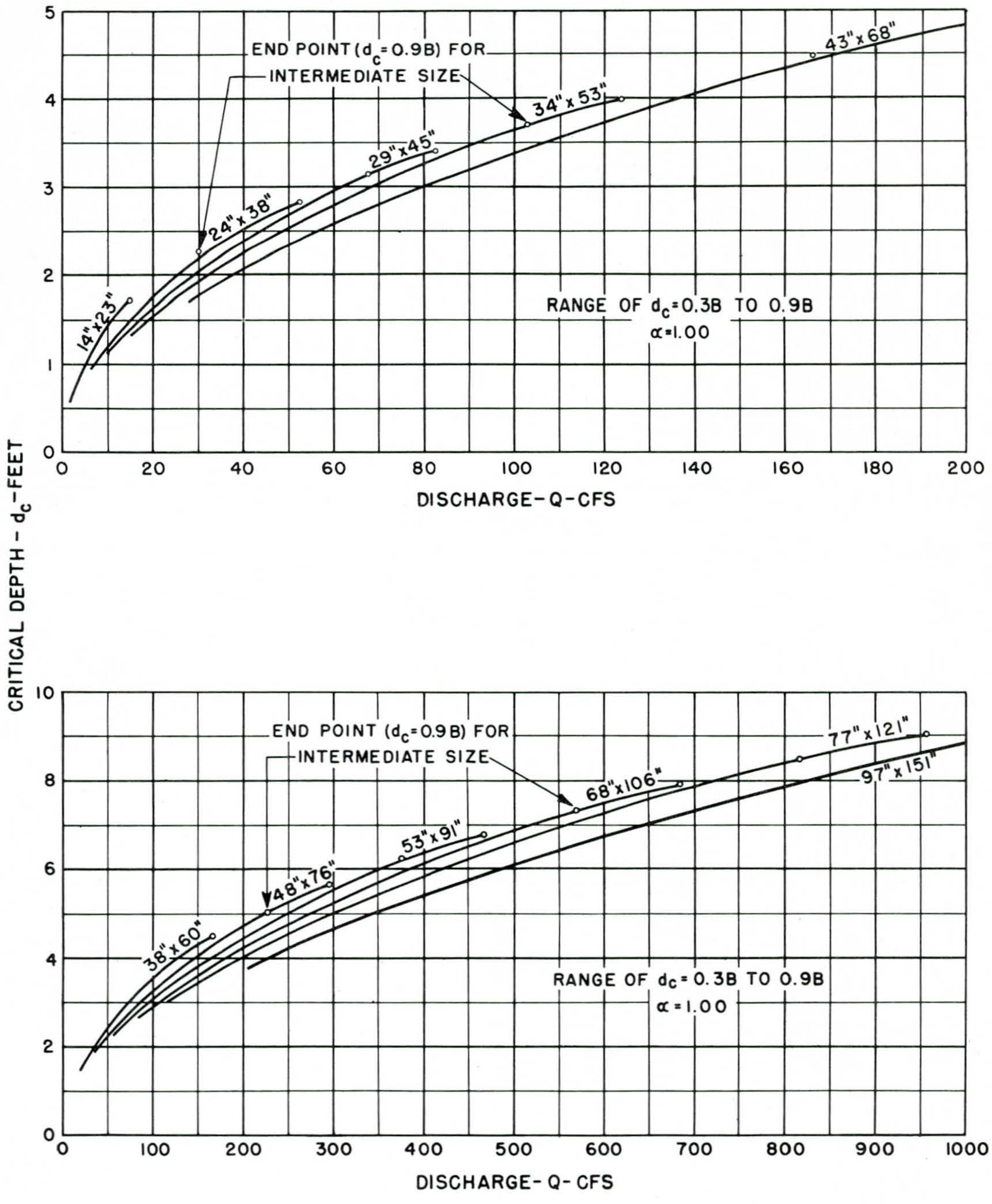
OVAL CONCRETE PIPE
LONG AXIS HORIZONTAL
SPECIFIC HEAD AT CRITICAL DEPTH

CHART 79



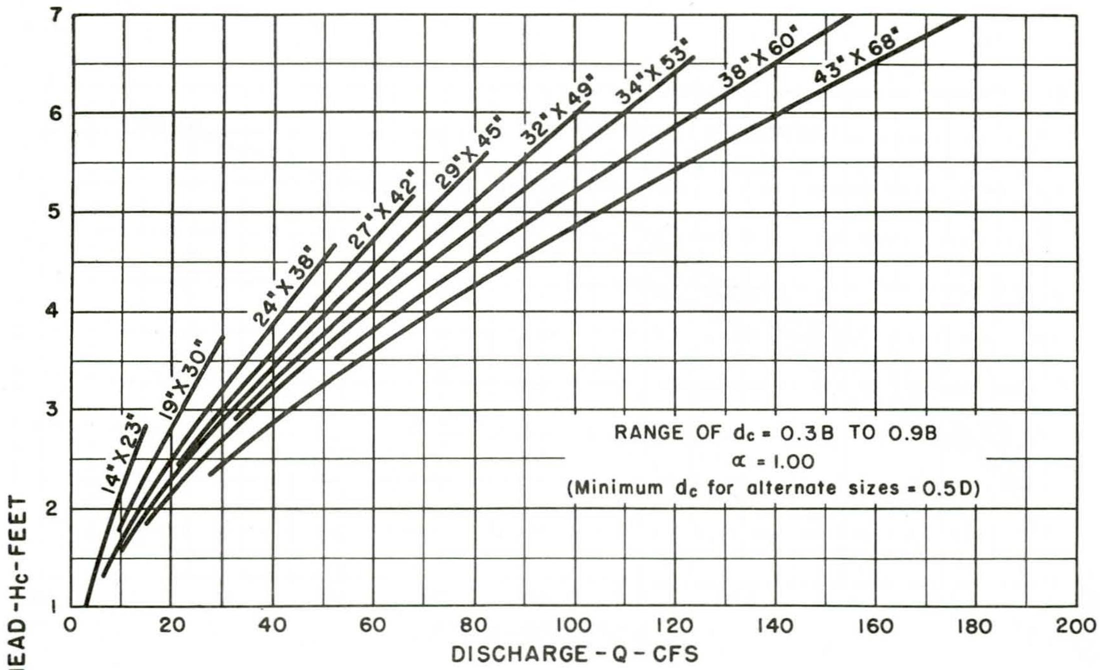
OVAL CONCRETE PIPE
LONG AXIS HORIZONTAL
CRITICAL SLOPE
n = 0.011

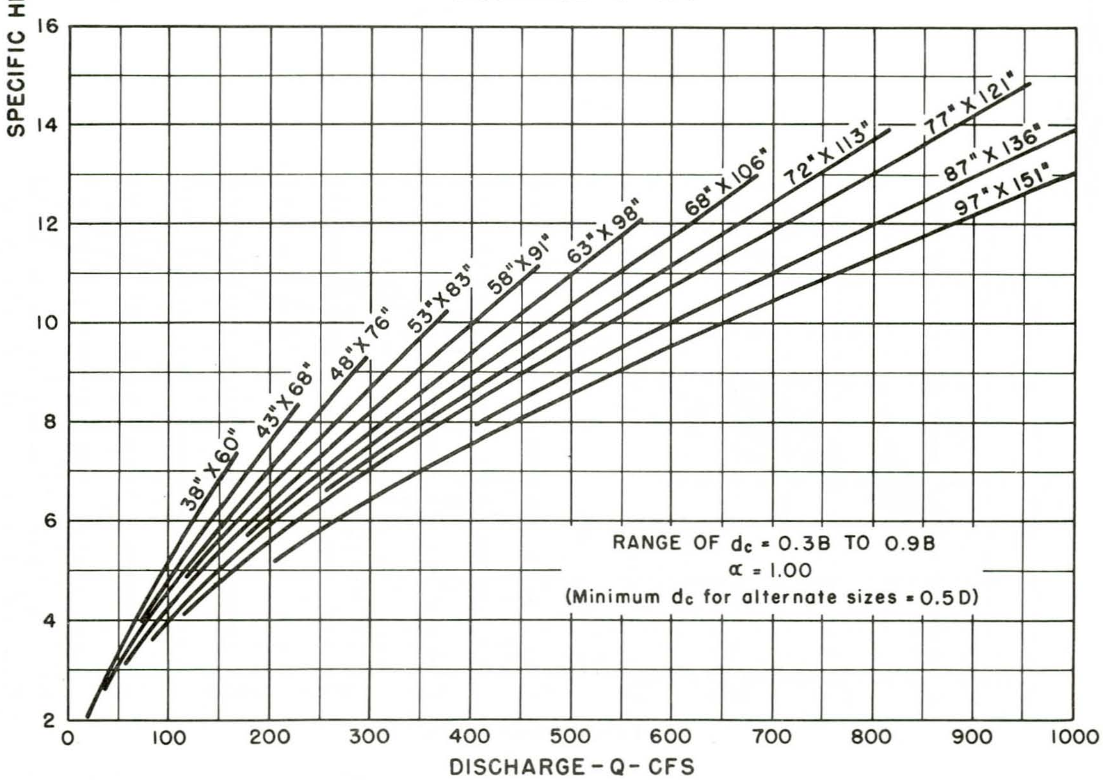
CHART 80



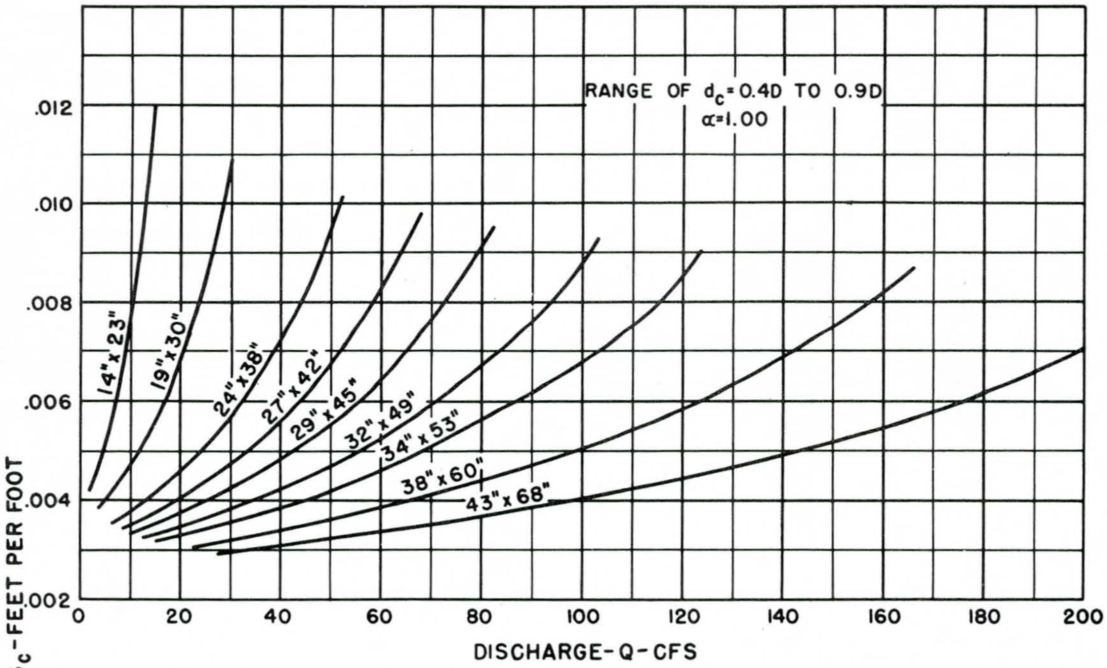
OVAL CONCRETE PIPE
LONG AXIS VERTICAL
CRITICAL DEPTH

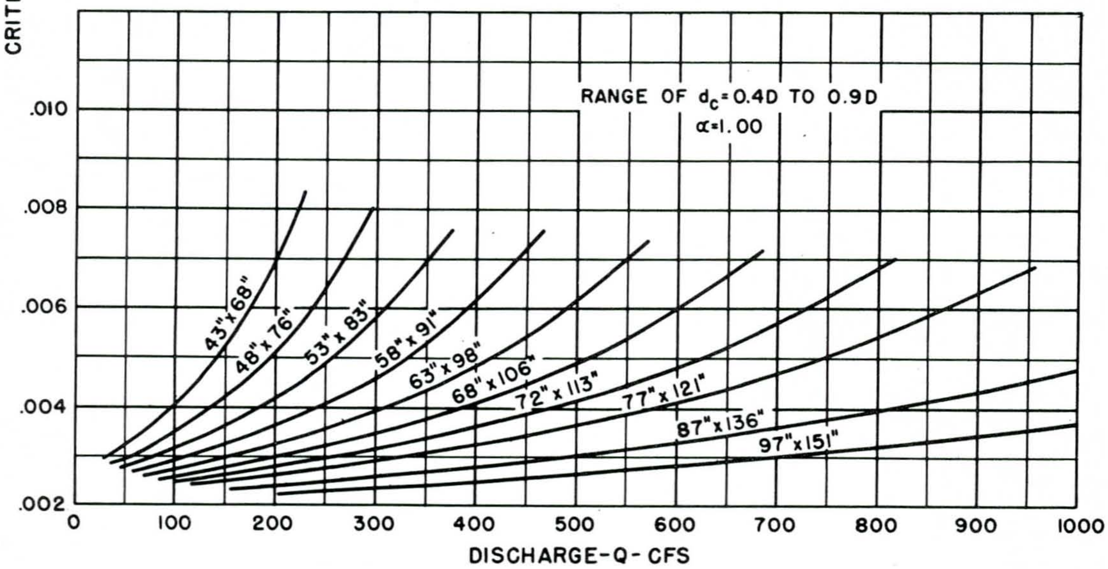
CHART 81





OVAL CONCRETE PIPE
LONG AXIS VERTICAL
SPECIFIC HEAD AT CRITICAL DEPTH





OVAL CONCRETE PIPE
LONG AXIS VERTICAL
CRITICAL SLOPE
n = 0.011

Appendix A.—TABLES

Table 1.—Manning roughness coefficients, *n* [1]

	Manning's *n* range [2]
I. Closed conduits:	
A. Concrete pipe	0.011–0.013
B. Corrugated-metal pipe or pipe-arch:	
1. 2⅔ by ½-in. corrugation (riveted pipe): [3]	
a. Plain or fully coated	0.024
b. Paved invert (range values are for 25 and 50 percent of circumference paved):	
(1) Flow full depth	0.021–0.018
(2) Flow 0.8 depth	0.021–0.016
(3) Flow 0.6 depth	0.019–0.013
2. 6 by 2-in. corrugation (field bolted)	0.03
C. Vitrified clay pipe	0.012–0.014
D. Cast-iron pipe, uncoated	0.013
E. Steel pipe	0.009–0.011
F. Brick	0.014–0.017
G. Monolithic concrete:	
1. Wood forms, rough	0.015–0.017
2. Wood forms, smooth	0.012–0.014
3. Steel forms	0.012–0.013
H. Cemented rubble masonry walls:	
1. Concrete floor and top	0.017–0.022
2. Natural floor	0.019–0.025
I. Laminated treated wood	0.015–0.017
J. Vitrified clay liner plates	0.015
II. Open channels, lined [4] (straight alinement): [5]	
A. Concrete, with surfaces as indicated:	
1. Formed, no finish	0.013–0.017
2. Trowel finish	0.012–0.014
3. Float finish	0.013–0.015
4. Float finish, some gravel on bottom	0.015–0.017
5. Gunite, good section	0.016–0.019
6. Gunite, wavy section	0.018–0.022
B. Concrete, bottom float finished, sides as indicated:	
1. Dressed stone in mortar	0.015–0.017
2. Random stone in mortar	0.017–0.020
3. Cement rubble masonry	0.020–0.025
4. Cement rubble masonry, plastered	0.016–0.020
5. Dry rubble (riprap)	0.020–0.030
C. Gravel bottom, sides as indicated:	
1. Formed concrete	0.017–0.020
2. Random stone in mortar	0.020–0.023
3. Dry rubble (riprap)	0.023–0.033
D. Brick	0.014–0.017
E. Asphalt:	
1. Smooth	0.013
2. Rough	0.016
F. Wood, planed, clean	0.011–0.013
G. Concrete-lined excavated rock:	
1. Good section	0.017–0.020
2. Irregular section	0.022–0.027
III. Open channels, excavated [4] (straight alinement,[5] natural lining):	
A. Earth, uniform section:	
1. Clean, recently completed	0.016–0.018
2. Clean, after weathering	0.018–0.020
3. With short grass, few weeds	0.022–0.027
4. In gravelly soil, uniform section, clean	0.022–0.025
B. Earth, fairly uniform section:	
1. No vegetation	0.022–0.025
2. Grass, some weeds	0.025–0.030
3. Dense weeds or aquatic plants in deep channels	0.030–0.035
4. Sides clean, gravel bottom	0.025–0.030
5. Sides clean, cobble bottom	0.030–0.040
C. Dragline excavated or dredged:	
1. No vegetation	0.028–0.033
2. Light brush on banks	0.035–0.050
D. Rock:	
1. Based on design section	0.035
2. Based on actual mean section:	
a. Smooth and uniform	0.035–0.040
b. Jagged and irregular	0.040–0.045
E. Channels not maintained, weeds and brush uncut:	
1. Dense weeds, high as flow depth	0.08–0.12
2. Clean bottom, brush on sides	0.05–0.08
3. Clean bottom, brush on sides, highest stage of flow	0.07–0.11
4. Dense brush, high stage	0.10–0.14

	Manning's *n* range [2]
IV. Highway channels and swales with maintained vegetation [6 7] (values shown are for velocities of 2 and 6 f.p.s.):	
A. Depth of flow up to 0.7 foot:	
1. Bermudagrass, Kentucky bluegrass, buffalograss:	
a. Mowed to 2 inches	0.07–0.045
b. Length 4–6 inches	0.09–0.05
2. Good stand, any grass:	
a. Length about 12 inches	0.18–0.09
b. Length about 24 inches	0.30–0.15
3. Fair stand, any grass:	
a. Length about 12 inches	0.14–0.08
b. Length about 24 inches	0.25–0.13
B. Depth of flow 0.7–1.5 feet:	
1. Bermudagrass, Kentucky bluegrass, buffalograss:	
a. Mowed to 2 inches	0.05–0.035
b. Length 4 to 6 inches	0.06–0.04
2. Good stand, any grass:	
a. Length about 12 inches	0.12–0.07
b. Length about 24 inches	0.20–0.10
3. Fair stand, any grass:	
a. Length about 12 inches	0.10–0.06
b. Length about 24 inches	0.17–0.09
V. Street and expressway gutters:	
A. Concrete gutter, troweled finish	0.012
B. Asphalt pavement:	
1. Smooth texture	0.013
2. Rough texture	0.016
C. Concrete gutter with asphalt pavement:	
1. Smooth	0.013
2. Rough	0.015
D. Concrete pavement:	
1. Float finish	0.014
2. Broom finish	0.016
E. For gutters with small slope, where sediment may accumulate, increase above values of *n* by	*0.002*
VI. Natural stream channels: [8]	
A. Minor streams [9] (surface width at flood stage less than 100 ft.):	
1. Fairly regular section:	
a. Some grass and weeds, little or no brush	0.030–0.035
b. Dense growth of weeds, depth of flow materially greater than weed height	0.035–0.05
c. Some weeds, light brush on banks	0.035–0.05
d. Some weeds, heavy brush on banks	0.05–0.07
e. Some weeds, dense willows on banks	0.06–0.08
f. For trees within channel, with branches submerged at high stage, increase all above values by	*0.01–0.02*
2. Irregular sections, with pools, slight channel meander; increase values given in 1a–e about	*0.01–0.02*
3. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stage:	
a. Bottom of gravel, cobbles, and few boulders	0.04–0.05
b. Bottom of cobbles, with large boulders	0.05–0.07
B. Flood plains (adjacent to natural streams):	
1. Pasture, no brush:	
a. Short grass	0.030–0.035
b. High grass	0.035–0.05
2. Cultivated areas:	
a. No crop	0.03–0.04
b. Mature row crops	0.035–0.045
c. Mature field crops	0.04–0.05
3. Heavy weeds, scattered brush	0.05–0.07
4. Light brush and trees: [10]	
a. Winter	0.05–0.06
b. Summer	0.06–0.08
5. Medium to dense brush: [10]	
a. Winter	0.07–0.11
b. Summer	0.10–0.16
6. Dense willows, summer, not bent over by current	0.15–0.20
7. Cleared land with tree stumps, 100–150 per acre:	
a. No sprouts	0.04–0.05
b. With heavy growth of sprouts	0.06–0.08
8. Heavy stand of timber, a few down trees, little undergrowth:	
a. Flood depth below branches	0.10–0.12
b. Flood depth reaches branches	0.12–0.16
C. Major streams (surface width at flood stage more than 100 ft.): Roughness coefficient is usually less than for minor streams of similar description on account of less effective resistance offered by irregular banks or vegetation on banks. Values of *n* may be somewhat reduced. Follow recommendation in publication cited [8] if possible. The value of *n* for larger streams of most regular section, with no boulders or brush, may be in the range of	0.028–0.033

Footnotes to table 1 appear at the top of page 101.

Footnotes to Table 1

[1] Estimates are by Bureau of Public Roads unless otherwise noted.

[2] Ranges indicated for closed conduits and for open channels, lined or excavated, are for good to fair construction (unless otherwise stated). For poor quality construction, use larger values of n.

[3] *Friction Factors in Corrugated Metal Pipe*, by M. J. Webster and L. R. Metcalf, Corps of Engineers, Department of the Army; published in Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, vol. 85, No. HY9, Sept. 1959, Paper No. 2148, pp. 35–67.

[4] For important work and where accurate determination of water profiles is necessary, the designer is urged to consult the following references and to select n by comparison of the specific conditions with the channels tested:

Flow of Water in Irrigation and Similar Channels, by F. C. Scobey, Division of Irrigation, Soil Conservation Service, U.S. Department of Agriculture, Tech. Bull. No. 652, Feb. 1939; and

Flow of Water in Drainage Channels, by C. E. Ramser, Division of Agricultural Engineering, Bureau of Public Roads, U.S. Department of Agriculture, Tech. Bull. No. 129, Nov. 1929.

[5] With channel of an alinement other than straight, loss of head by resistance forces will be increased. A small increase in value of n may be made, to allow for the additional loss of energy.

[6] *Handbook of Channel Design for Soil and Water Conservation*, prepared by the Stillwater Outdoor Hydraulic Laboratory in cooperation with the Oklahoma Agricultural Experiment Station; published by the Soil Conservation Service, U.S. Department of Agriculture, Publ. No. SCS–TP–61, Mar. 1947, rev. June 1954.

[7] *Flow of Water in Channels Protected by Vegetative Linings*, by W. O. Ree and V. J. Palmer, Division of Drainage and Water Control, Research, Soil Conservation Service, U.S. Department of Agriculture, Tech. Bull. No. 967, Feb. 1949.

[8] For calculation of stage or discharge in natural stream channels, it is recommended that the designer consult the local District Office of the Surface Water Branch of the U.S. Geological Survey, to obtain data regarding values of n applicable to streams of any specific locality. Where this procedure is not followed, the table may be used as a guide. The values of n tabulated have been derived from data reported by C. E. Ramser (see footnote 4) and from other incomplete data.

[9] The tentative values of n cited are principally derived from measurements made on fairly short but straight reaches of natural streams. Where slopes calculated from flood elevations along a considerable length of channel, involving meanders and bends, are to be used in velocity calculations by the Manning formula, the value of n must be increased to provide for the additional loss of energy caused by bends. The increase may be in the range of perhaps 3 to 15 percent.

[10] The presence of foliage on trees and brush under flood stage will materially increase the value of n. Therefore, roughness coefficients for vegetation in leaf will be larger than for bare branches. For trees in channel or on banks, and for brush on banks where submergence of branches increases with depth of flow, n will increase with rising stage.

Table 2.—Permissible velocities for channels with erodible linings, based on uniform flow in continuously wet, aged channels [1]

Soil type or lining (earth; no vegetation)	Maximum permissible velocities for— Clear water	Water carrying fine silts	Water carrying sand and gravel
	F.p.s.	*F.p.s.*	*F.p.s.*
Fine sand (noncolloidal)	1.5	2.5	1.5
Sandy loam (noncolloidal)	1.7	2.5	2.0
Silt loam (noncolloidal)	2.0	3.0	2.0
Ordinary firm loam	2.5	3.5	2.2
Volcanic ash	2.5	3.5	2.0
Fine gravel	2.5	5.0	3.7
Stiff clay (very colloidal)	3.7	5.0	3.0
Graded, loam to cobbles (noncolloidal)	3.7	5.0	5.0
Graded, silt to cobbles (colloidal)	4.0	5.5	5.0
Alluvial silts (noncolloidal)	2.0	3.5	2.0
Alluvial silts (colloidal)	3.7	5.0	3.0
Coarse gravel (noncolloidal)	4.0	6.0	6.5
Cobbles and shingles	5.0	5.5	6.5
Shales and hard pans	6.0	6.0	5.0

[1] As recommended by Special Committee on Irrigation Research, American Society of Civil Engineers, 1926.

Table 3.—Permissible velocities for channels lined with uniform stands of various grass covers, well maintained [1 2]

Cover	Slope range	Permissible velocity on— Erosion resistant soils	Easily eroded soils
	Percent	*F.p.s.*	*F.p.s.*
Bermudagrass	0–5	8	6
	5–10	7	5
	Over 10	6	4
Buffalograss, Kentucky bluegrass, Smooth brome, Blue grama	0–5	7	5
	5–10	6	4
	Over 10	5	3
Grass mixture	0–5	5	4
	5–10	4	3
Lespedeza sericea, Weeping lovegrass, Yellow bluestem, Kudzu, Alfalfa, Crabgrass	0–5	3.5	2.5
Common lespedeza [3], Sudangrass [3]	[4] 0–5	3.5	2.5

[1] From *Handbook of Channel Design for Soil and Water Conservation* (see footnote 6, table 1, above).

[2] Use velocities over 5 f.p.s. only where good covers and proper maintenance can be obtained.

[3] Annuals, used on mild slopes or as temporary protection until permanent covers are established.

[4] Use on slopes steeper than 5 percent is not recommended.

Table 4.—Factors for adjustment of discharge to allow for increased resistance caused by friction against the top of a closed rectangular conduit [1]

D/B	Factor
1.00	1.21
.80	1.24
.75	1.25
.667	1.27
.60	1.28
.50	1.31
.40	1.34

[1] Interpolations may be made. See derivation of factors on p. 8.

Table 5.—Guide to selection of retardance curve

Average length of vegetation	Retardance curve for— Good stand	Fair stand
6–10 inches	C.	D.
2–6 inches	D.	D.

Appendix B.—CONSTRUCTION OF DESIGN CHARTS FOR OPEN-CHANNEL FLOW

B.1 Charts with Manning's n constant. Design charts for open-channel flow, such as those presented in chapter 3, are plotted on logarithmic paper. Each chart is constructed for a fixed cross section and a given value of Manning's n by the following steps. Table B–1 serves as an illustrative example. (See note at end of section.)

1. Prepare a table with column headings as shown in table B–1.

2. Tabulate desired increments of depth in the first column.

3. Compute A, WP, $R=A/WP$, $R^{2/3}$, T, and $d_m=A/T$ for each depth.

4. Using Manning's equation:

$$V=\frac{1.49}{n}R^{2/3}S^{1/2}$$

and the given value of n, compute V for a slope of $S=0.01$, for each depth.

5. From the values of V, derived in step 4, compute values for $Q=AV$.

6. Compute values of V and Q for $S=0.10$ for each depth, by multiplying the tabulated values of V and Q for $S=0.01$ by the factor $(0.10/0.01)^{1/2}=3.162$. Similarly, compute values of V and Q for $S=0.001$ for each depth, by multiplying the tabulated values of V and Q for $S=0.01$ by the factor $(0.001/0.01)^{1/2}=0.3162$.

7. On logarithmic paper with a sufficient number of cycles, plot V against Q for $S=0.01$, 0.10, and 0.001. Note the value of the corresponding depth, using a small number written alongside each plotted point.

8. Draw a smooth curve through the points for each slope. A point not falling on this smooth curve presumably indicates that an error has been made either in computing or in plotting.

9. Draw straight lines through points of equal depth. This provides another check on the accuracy of computing and plotting. These equal-depth lines must be straight, since the equation is $V=Q/A$, where A is a constant for a given depth.

10. The graph now has all the depth lines but only three slope lines. Other slope lines may be laid out by marking off a logarithmic scale along enough depth lines to define the slight curvature in the slope lines. The length of the log cycle is the distance between either two of the three slope curves already drawn, and will be the same along any depth line. A simple graphic device to obtain the logarithmic spacing for any length of cycle can be made by laying off a log scale along the leg of a right triangle with a long base line, and then drawing straight lines from the divisions on the scale to the opposite vertex. The spacing of these lines along any line laid across them will be logarithmic and it is merely necessary to position the triangle so that the distance from the base to a point on the hypotenuse corresponds to the length of cycle desired.

11. Critical curves are an essential part of the charts. For plotting points, compute, for each depth, $gd_m=32.2\ d_m$ and tabulate. (d_m has already been tabulated in the table.) Next compute, for each depth, $V_c=(gd_m)^{1/2}$.

Table B–1.—Sample computations for channel-flow chart: Trapezoidal channel, 1:1 side slopes, 10-foot bottom width, $n=0.03$

d	A	WP	R	$R^{2/3}$	T	d_m	For $S=0.01$		For $S=0.10$		For $S=0.001$		Critical curve	
							V	Q	V	Q	V	Q	gd_m	V_c
Ft.	*Sq. ft.*	*Ft.*	*Ft.*		*Ft.*	*Ft.*								
0.2	2.04	10.57	0.193	0.334	10.4	0.1962	1.65	3.37	5.23	10.7	0.523	1.07	6.318	2.51
.4	4.16	11.13	.374	.519	10.8	.3852	2.57	10.7	8.13	33.8	.813	3.38	12.40	3.52
.6	6.36	11.70	.544	.666	11.2	.5679	3.30	21.0	10.4	66.4	1.04	6.64	18.29	4.28
1.0	11.00	12.83	.857	.902	12.0	.9167	4.47	49.1	14.1	155	1.41	15.5	29.52	5.43
1.5	17.25	14.24	1.211	1.137	13.0	1.327	5.63	97.2	17.8	307	1.78	30.7	42.73	6.54
2.0	24.00	15.66	1.533	1.330	14.0	1.714	6.59	158	20.8	500	2.08	50.0	55.19	7.43
2.5	31.25	17.07	1.831	1.497	15.0	2.083	7.42	232	23.4	733	2.34	73.3	67.07	8.19
3.0	39.00	18.48	2.110	1.645	16.0	2.438	8.15	318	25.8	1,000	2.58	100	78.50	8.86
3.5	47.25	19.90	2.375	1.779	17.0	2.779	8.81	416	27.9	1,320	2.79	132	89.48	9.46
4.0	56.00	21.31	2.627	1.904	18.0	3.111	9.43	528	29.8	1,670	2.98	167	100.2	10.0
5.0	75.00	24.14	3.107	2.129	20.0	3.750	10.5	791	33.3	2,500	3.34	250	120.8	11.0
6.0	96.00	26.97	3.560	2.331	22.0	4.364	11.5	1,110	36.5	3,510	3.65	350	140.5	11.8
7.0	119.0	29.80	3.993	2.517	24.0	4.958	12.5	1,480	39.4	4,690	3.94	469	159.6	12.6
8.0	144.0	32.63	4.414	2.691	26.0	5.538	13.3	1,920	42.2	6,070	4.22	607	178.3	13.4
10.0	200.0	38.28	5.224	3.011	30.0	6.667	14.9	2,980	47.2	9,430	4.72	943	214.7	14.6

Plotting points of intersection of $V=V_c$ with respective depth lines locates the critical curve.

12. The usefulness of the chart many be expanded by adding scales along the ordinate and the abscissa, corresponding to the products Vn and Qn, respectively. It must be borne in mind, however, that the critical curve may be used only with the value of n for which the chart was drawn.

Note: Computations in steps 3 and 4 for many channel sections can be found in the Corps of Engineers *Hydraulic Tables* and the Bureau of Reclamation *Hydraulic and Excavation Tables.*[1]

B.2 Charts for grassed channels with *n* variable. Design charts for open-channel flow in grassed channels, such as those presented in chapter 4, are computed by the Manning equation with n varying as a function of VR (see fig. 5, p. 38). On these charts the ordinate is channel slope S and the abscissa is discharge Q. For a given cross section, each depth and velocity curve must be computed separately according to the following steps. Table B–2 serves as an illustrative example.

1. Prepare tables with column headings as shown in table B–2. Select desired increments of depth. A separate table is required for each depth.

2. For each depth d, compute A, WP, $R=A/WP$, T, $d_m=A/T$, $R^{2/3}$, and $(1.49R^{2/3})^2$. Arrange these constants at the top of the table.[2]

3. Select desired increments of velocity, usually 0.5 f.p.s. and 1 to 10 f.p.s. by units of one, and list in the first column of the table.

4. Replot the appropriate retardance curve from figure 5 on logarithmic paper. The purpose of this is to obtain consistent readings of n, so that the velocity curves to be plotted later will be smooth curves. (This does not mean, however, that velocities determined in the completed graph are actually that accurate, since the true value of retardance may vary considerably.)

5. For each selected depth (that is, in each table being computed for a selected increment of d):

5a. Compute VR for each velocity V, and tabulate.

5b. From the retardance curve plotted as step 4, read and tabulate n for each value of VR.

5c Compute $(Vn)^2$.

5d. Compute and tabulate $S=(Vn)^2\div(1.49R^{2/3})^2$. The denominator has already been computed as one of the constants.

5e. Compute and tabulate $Q=AV$.

6. Select logarithmic graph paper having sufficient cycles to cover the desired range of Q and S, and for each depth:

6a. Plot S against Q for each velocity; label each plotted point with the corresponding value of V.

[1] See footnote 1, p. 3.

[2] The value $(1.49R^{2/3})^2=2.2082R^{4/3}$. A table of values for the reciprocal of the latter will be found in *Handbook of Hydraulics, for the Solution of Hydraulic Problems*, by H. W. King, revised by E. F. Brater, McGraw-Hill Book Co., 1954. (See table 107 in 3d edition or table 91 in 4th edition.)

Table B–2.—Computations for grassed channel:[1] Trapezoidal channel, 8:1 side slopes, $b=4$, retardance C

CONSTANTS

$d=0.8$	$R=0.491$	$R^{2/3}=0.621$
$A=8.32$	$T=16.84$	$(1.49R^{2/3})^2=0.857$
$WP=16.94$	$d_m=0.494$	

V	VR	n	$(Vn)^2$	S	Q
F.p.s.	*Ft.²/sec*			*Ft./ft.*	*C.f.s.*
0.5	0.246	0.225	0.0127	0.0148	4.16
1	.491	.135	.0182	.0212	8.32
2	.982	.084	.0282	.0327	16.6
3	1.473	.067	.0404	.0471	25.0
4	1.964	.057	.0520	.0607	33.3
5	2.455	.052	.0676	.0789	41.6
6	2.946	.047	.0795	.0928	49.9
7	3.437	.044	.0949	.111	58.2
8	3.938	.043	.1183	.138	66.6
9	4.419	.041	.1362	.159	74.9
10	4.910	.040	.1600	.187	83.2
$V_c=3.99$	1.96	0.057	0.0517	0.0603	33.20

[1] Similar computations must be made for each selected depth.

6b. Draw a curve for each depth through the plotted points. This should be a smoothly curving line. A point not falling on the curve presumably indicates that an error has been made either in computing or in reading the n values.

7. Connect lines of equal velocity, which again should be smoothly curving lines. Points will not fit perfectly because of minor discrepancies in reading the retardance curve, but wide variations indicate major errors in computation.

8. Critical slope is calculated for each depth as follows; the computed values being entered across the bottom of the table as shown in table B–2:

8a. Compute $V_c=(gd_m)^{1/2}$.

8b. Compute V_cR.

8c. Read from the retardance curve the value of n for V_cR.

8d. Solve for slope S_c as in step 5d.

8e. Compute $Q_c=AV_c$.

9. Plot critical slope S_c against Q_c for each depth, and draw a smooth curve through the points.

10. Examine the plotted curves for consistency. If equal increments of depth and velocity have been used, curves should show a systematic change in spacing, becoming closer as depth increases or velocity increases, as the case may be. At any point of intersection of depth and velocity curves, the product AV must equal the value of Q read for that point.

11. Changes in retardance must be taken into account. Unlike the open-channel charts for a fixed value of n, where a single chart may be used for other values of n, the grassed channel chart must be replotted for a different retardance. However, only two additional columns are required in the computation table: the n for the new retardance and the solution for S as in step 5d. The new S is then plotted against Q as previously calculated (in step 5e), to obtain a new set of curves for this retardance.

Appendix C.—GRAPHIC SOLUTION OF THE MANNING EQUATION

Chart 83 is a nomograph for the solution of the Manning equation:

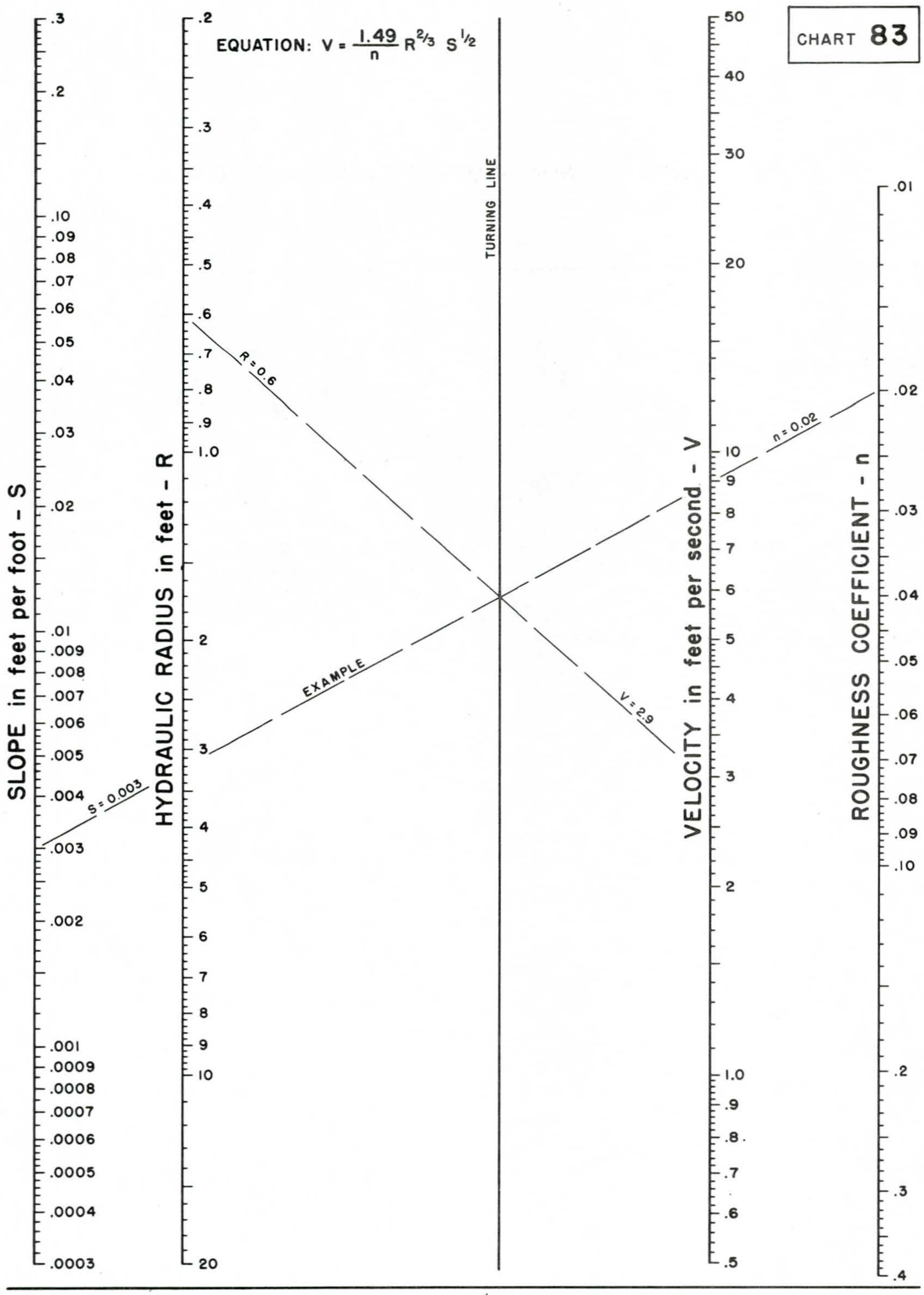
$$V=\frac{1.49}{n} R^{2/3} S^{1/2}.$$

This chart will be found useful when an open-channel flow chart is not available for the particular channel cross section under consideration. Values of n will be found in table 1, and slope S and hydraulic radius $R=A/WP$, where A is the area of cross section and WP is the wetted perimeter, are dimensions of the channel.

Use of the chart is demonstrated by the example shown on the chart itself. Given is a channel with rectangular cross section, 6 feet wide, flowing at a depth of 0.75 foot, with a 0.3-percent slope ($S=0.003$), and $n=0.02$. Area $A=6\times 0.75=4.50$ sq. ft.; wetted perimeter $WP=6+2\times 0.75=7.50$ ft.; then $R=A/WP=4.50/7.50=0.6$.

A straight line is laid on the chart, connecting $S=0.003$ and $n=0.02$. Another straight line is then laid on the chart, connecting $R=0.6$ and the intersection of the first line and the "turning line," and extending to the velocity scale. Reading this scale, $V=2.9$.

The chart may, of course, be used to find any one of the four values represented, given the other three; and may also be used for channels with cross sections other than rectangular.



NOMOGRAPH FOR SOLUTION OF MANNING EQUATION

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