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Stability Design of Grass-Lined Open Channels

ABSTRACT

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This handbook presents the state of the art in grass-lined channel design. It is intended primarily for use by engineers and technicians directly involved in planning, designing, or maintaining open channels where vegetation can be used as a lining for erosion protection. Each of the six chapters is a complete discussion, with reference to other chapters as appropriate. Nomographs and calculator/computer programs are included as design aids. Only those design conditions that have implications unique to the use of grass as a channel lining are discussed in detail, and the design aids focus on stability design under steady, uniform flow conditions.

KEYWORDS: grass linings, open channel hydraulics, agricultural waterways, lined channels, erosion

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Stability Design of Grass-Lined Open Channels

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PREFACE

Grass linings have been widely used for agricultural waterways for many years. The U.S. Department of Agriculture's Soil Conservation Service (USDA, SCS) developed an empirical permissible velocity procedure for the design of these waterways that was published in revised form in 1954 as SCS TP-61 (SCS 1954). This publication has been the basis for most grass-lined channel design since that time.

In the late 1970's, renewed interest in grass linings for use in floodways, urban drainageways, and reservoir emergency spillways led to a reanalysis of the available data and a better understanding of the interaction of the flow with a vegetated boundary. The effective stress design approach resulting from this reanalysis, although still semiempirical, improved the separation of independent variables in the design relations. Combining this approach with appropriate soil erodibility relations results in improved design procedures which are more flexible than the permissible velocity based procedures and which are consistent with current nonvegetated channel design practices.

This handbook presents the state-of-the-art in grassed waterway design. Only those design conditions which have implications unique to the use of grass as a channel lining are discussed in detail. Relations routinely applied to rigid boundary or unlined channels are presented with little or no comment, because we assume that an individual wishing to use the material in this handbook will already be familiar with the basic principles of open channel hydraulics. Dimensionally dependent relations are presented in English units only; a metric-unit version may be purchased from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

Since the design relations and examples are presented in the general context of steady uniform flow, additional references will be needed for hydraulically complex conditions. An attractive point of effective stress analysis, however, is that more hydraulically complex conditions may be approached the same for lined and unlined channels. Procedures based on conservation of momentum or energy should use the appropriate coefficients as discussed herein.

This handbook is intended for use primarily by engineers and technicians in planning, designing, or maintaining open channels where vegetation can be used as a lining for erosion protection. Because not all users will wish to study the entire text in detail, each of the six chapters is presented as a complete discussion, with reference made to other chapters as appropriate. Figures and tables are cross-referenced rather than repeated.

Chapter 1 discusses the theory and logic underlying the effective stress approach to the design of vegetated channels. Limitations of the approach are also discussed. The contents of this chapter should be understood by engineers faced with unusual design conditions and/or those conditions which may not be well represented in the data base.

Chapter 2 addresses the essential agronomic considerations in selecting, establishing, and maintaining grass channel linings. This chapter is intended as a first reference when considering grass as a channel lining. In many instances, it will be desirable to consult a qualified agronomist familiar with local conditions before finalizing a design.

Chapter 3 will be used routinely to estimate design parameters after soil and cover types have been identified. Although the design aids presented in this chapter may be used in "cookbook" fashion, an understanding of the flow behavior as discussed in chapter 1 is desirable. It is in the estimation of these parameters that engineering judgment enters the design process. For properly maintained channels, designs based on direct use of the tables and graphs provided in these chapters will usually result in conservative designs. Rational modification of the estimated values based on a knowledge of local conditions and an understanding of the flow-boundary interaction will, therefore, have the potential of decreasing costs.

The numerical effective stress design procedure is presented in chapter 4, along with examples of its application. The procedure may be used directly in hand calculations, but is best suited for programmed calculator or computer application. Programs may be developed directly from the procedure described here, or sample computational routines in chapter 5 may be used.

Chapter 6 consists of a limited set of graphical design aids for rapid estimation of channel stability. Use of these curves requires less initial information than the numerical procedure and does not require the use of a calculator or computer to determine limiting conditions. When both procedures are applied correctly, however, the required channel cross-sectional area associated with the numerical procedure will usually be slightly less than that estimated using the graphical approach.

The numerical expressions and design aids presented in these chapters are directly applicable to open channels lined with a relatively uniform grass cover. When the vegetal cover is very nonuniform, a more detailed flow analysis and/or engineering judgment will usually be required. A thorough understanding of basic hydraulic principles and the concepts discussed in chapter 1 will allow such judgment to be applied rationally.

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CONTENTS

1. DEVELOPMENT OF DESIGN RELATIONS

By D.M. Temple

The design relations discussed in this chapter were developed from physical principles, experience, and laboratory data. They represent a semiempirical dominant process model which is internally consistent and well suited for use as a design tool. Because the relations represent a semiempirical simplification of a complex process, the limits imposed by the simplifying assumptions and the data base will be discussed, even though these limits will seldom be approached in design problems. The procedure for applying the relations to design problems is described in chapters 3 and 4.

FLOW RESISTANCE

Flow resistance of an open channel is a result of viscous and pressure drag over its wetted perimeter. For a vegetated channel, this drag may be conceptually divided into three components. They are (1) the sum of viscous drag on the soil surface and pressure drag on soil particles or aggregates small enough to be individually moved by the flow (soil grain roughness), (2) pressure drag associated with large nonvegetal boundary roughness (form roughness), and (3) drag on the vegetal elements (vegetal roughness). Since these forces act directly on the moving fluid in opposition to the local velocity vector, it is equally valid, and sometimes more convenient, to discuss the flow-boundary interaction in terms of the energy expended in moving the fluid against each component force rather than directly in terms of the component forces. Whichever approach is taken (both will be used in the discussions which follow), the conceptual division remains the same, and the key to understanding the flow behavior is recognizing that the flow and the boundary interact. Neither may be considered entirely independent of the other when considering flow resistance or channel stability.

Interaction of the boundary with the flow field causes the effective boundary roughness of a grass-lined channel to become a function of flow conditions. Flow resistance coefficients that are treated as constants under changing flow conditions for rigid boundary applications will, therefore, not remain constant for the case of a grass boundary. This will be true for any of the flow equations traditionally used in hydraulic applications.

The flow equation that will be used throughout this handbook is Manning's equation, which may be written as:

$$V = \frac{1.49}{n} R^{2/3} S^{1/2} \tag{1.1}$$

in which V = the mean velocity at the cross section in feet per second,
R = the hydraulic radius in feet,
S = the energy slope at the cross section, and
n = Manning's resistance coefficient.

This equation was selected for use here primarily because of its widespread acceptance for open channel applications involving both rigid and natural boundaries.

Velocity Profile

For most grass-lined channels, drag on the vegetal elements dominates the flow resistance. Correct interpretation of flow resistance behavior therefore requires an understanding of the interaction of the flexible vegetal elements with the flow field.

Ree (1949) identified three distinct flow regions that become apparent when flow resistance for a given channel is plotted against depth or discharge. The apparent behavior of the velocity profile, as illustrated in figure 1.1 for each of these regions, is further discussed by Temple (1982). For the very low flows represented by figure 1.1a, the depth of flow is less than the deflected grass height and the local velocity is primarily dependent on the local vegetal density. Increases in flow depth less than that required to overtop the vegetation cause little change in mean velocity. Therefore, the flow resistance expressed in terms of traditional parameters such as Manning's n will tend to increase with increasing depth or discharge. Since the mean flow velocity at any cross section is directly related to the percentage of the cross section blocked by vegetal elements and the uniformity of their spacing, type of vegetation and quality of stand would be expected to dominate any resistance function for this region.

For the intermediate flows represented by figure 1.1b, the flow depth is greater than the deflected height of the grass. The vegetal elements tend to align themselves with the flow and exhibit a waving action. This waving action appears to continue as a result of turbulent interaction (lift and drag fluctuations associated with turbulence) long after structural hinge points have developed in the elements. Leaf structure becomes less important as the elements become better aligned with the flow. Increases in flow depth in this region result in a decrease in the thickness of the boundary zone dominated by vegetal action and an associated large increase in mean velocity. Therefore, flow resistance expressed in terms of Manning's n decreases with increasing depth or discharge. The vegetal parameters expected to dominate the resistance function under these conditions are the number of stems[1] and the length of each which drags in the flow. Stem diameter and stiffness would be expected to exert a secondary influence.

For the large flows represented by figure 1.1c, the depth of flow is much greater than the deflected height of the vegetation. As the depth increases and thickness of the boundary zone approaches a minimum, the portion of the flow passing through the vegetation becomes negligible compared to that flowing above, and the flow resistance of the grass expressed in terms of Manning's n tends to be a constant. Since the minimum boundary zone thickness depends primarily on the bulk of the material present and the growth characteristics of the vegetation near the bed, these variables would be expected to dominate the flow resistance function in this region.

Most practical problems related to stability design of grass-lined open channels concern flows in the intermediate-flow range. Discharges less than those required to submerge the vegetation seldom will generate significant sustained erosion, and stability limits are generally exceeded before the boundary zone thickness becomes negligible. The intermediate-flow range will, therefore, be assumed in the following discussions. Because reliable physically based resistance relations are not readily available for the very high or low flows, a constant value of Manning's n equal to its value at the nearest mathematically specified boundary (see eq. 1.2a) is usually assumed when an estimate outside the intermediate flow range is required. Although this may represent the best estimation available, the preceding discussion demonstrates that this approach will fail to recognize the proper dominant variables. This is particularly true for the very low flows.

Retardance Relations

When consideration is limited to the intermediate-flow region, Ree and Palmer (1949) showed that for given cover and boundary conditions, Manning's n could reasonably be expressed as a unique function of the product of mean velocity and hydraulic

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[1] The term "stem" is used here to identify those vegetal elements that act relatively independently in the flow. This will usually correspond reasonably well to a layman's definition of a stem. Stem length is measured from the point of contact with the soil to the stem tip.

radius.[2] The "n-VR" curves presented by the SCS (1954) are expressions of this functional relationship obtained by graphically fitting the available data.

A reanalysis of the data by Temple (1980, 1983) resulted in the general retardance relation given by:

$$n_R = \exp\{C_I(0.0133[\ln(VR)]^2 - 0.0954\ln(VR) + 0.297) - 4.16\} \tag{1.2}$$

with the limits of the intermediate flow range approximated by:

$$0.0025\ C_I^{2.5} \le VR \le 36 \tag{1.2a}$$

where n_R = a reference value of Manning's resistance coefficient applicable to vegetation established on relatively smoothly graded fine-grained soil,
C_I = the retardance curve index describing the retardance potential of the vegetal cover,
and V and R are as previously defined.

As indicated in the previous section, the vegetal flow resistance in the region of interest is primarily a result of drag along the entire length of the submerged stems, which have become more or less aligned with the flow. Analysis along these lines leads to an equation relating the empirical retardance curve index to measurable vegetal parameters given as (Temple 1982):

$$C_I = 2.5\ (h\sqrt{M})^{1/3} \tag{1.3}$$

in which h = the representative stem length in ft, and
M = the average stem density in stems per square foot.

This approach works well for grasses with well-defined stems, but becomes more difficult to apply for more brushy or branching vegetation such as alfalfa. Further discussion and design aids related to curve index parameter estimation are given in chapter 3.

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[2] More detailed analysis shows that the relation may be slightly improved by expressing n as a function of Reynold's number VR/ν. However, the uncertainty in the variables defining the vegetal cover is such that the improvement becomes statistically insignificant. Analysis based on the assumption of a constant kinematic viscosity is, therefore, considered justified.

To be consistent with the stress/energy balance assumptions to be discussed in the following section on effective soil stress, the component roughnesses expressed in terms of Manning's coefficient are related to each other and to the reference value n_R as (Temple 1980):

$$n = \sqrt{n_s^2 + n_\Psi^2 + n_V^2} \tag{1.4a}$$

which, for the data base of equation 1.2 reduces to:

$$n_R = \sqrt{(0.0156)^2 + 0^2 + n_V^2} \tag{1.4b}$$

yielding the general relation:

$$n = \sqrt{n_R^2 + n_s^2 + n_\Psi^2 - (0.0156)^2} \tag{1.4c}$$

where n = Manning's coefficient for the channel under the specified flow conditions.

n_s = Manning's coefficient associated with soil particles of a size capable of being detached by the flow at stability-limiting conditions (soil grain roughness).

n_Ψ = Manning's coefficient associated with boundary roughness elements other than vegetation which cannot be detached by the flow (boundary form roughness).

n_V = Manning's coefficient associated with the vegetation (vegetal roughness).

The constant 0.0156 in equation 1.4 is equal to the soil grain roughness for the fine-grained soils represented in the data base from which equation 1.2 was derived. Because large deviations of n_s and n_Ψ from their base values of 0.0156 (fine-grained soil) and 0.0 (prepared soil boundary resulting in negligible form roughness) are generally incompatible with the uniformity of cover required for an effective grass lining, variations in these parameters may often be ignored in the estimation of flow resistance. This allows equation 1.4c to be simplified to $n = n_R$ $(n_R^2 >> n_\Psi^2;\ n_R^2 >> n_s^2 - (0.0156)^2)$. The error associated with this simplification will often be less than that associated with the estimation of the vegetal parameters required for the determination of n_R.

The definition of the grain roughness given above is somewhat more exacting, and the definition of form roughness more general, than those in common use. These definitions are, however, the ones appropriate for application of the concepts to channel stability or sediment transport computations and are consistent with the discussions introducing these concepts into the literature (Einstein 1950). The treatment of grain roughness as a soil property is not inconsistent with these definitions, providing consideration is limited to conditions near incipient channel failure.

Momentum and Energy Coefficients

Closely related to the flow resistance behavior of the lining are the momentum and energy coefficients required for correct application of conservation principles. These coefficients are defined by the relations:

$$\alpha = \frac{\int v^3 dA}{V^3 A} \tag{1.5}$$

and

$$\beta = \frac{\int v^2 dA}{V^2 A} \tag{1.6}$$

Where α is the energy (Coriolis) coefficient, β is the momentum (Boussinesq) coefficient, v is the velocity at a point, dA is a differential area, and the integration is carried out over the cross section. Discussions of the general significance and application of these coefficients are in most texts on open channel flow.

For most open channel flow problems involving channels of regular cross section, the deviation of α or β from unity is relatively small, and the error in computed specific energy or specific force based on setting the coefficients equal to unity is within the uncertainty of the other variables involved. Although the available data for grass-lined channels is extremely limited, an examination of the velocity profiles shown in figure 1.1b shows that this is not true for the typical grass-lined channel condition. McCool (1970) reported observed values as high as 5 for the energy coefficient in an asymmetrical triangular channel lined with bermudagrass.

The importance of a coefficient of this magnitude may be seen by considering its influence on the Froude number, which is computed by the relation (Chow 1959):

$$F = \frac{V}{\sqrt{g \frac{A}{T} \frac{\cos\theta}{\alpha}}} \tag{1.7}$$

where F is the Froude number, g is the gravitational constant, θ is the bed slope angle, T is the channel width at the water surface, and the other variables are as previously defined.

Temple (1986) showed that the coefficients could be reasonably estimated by approximating the velocity profile by a constant velocity through the vegetal boundary zone and a modified Prandtl logarithmic velocity distribution above the boundary zone. Although this profile approximation is not acceptable for analysis of stress distribution involving the first derivative of the profile, it seems adequate for the problem of coefficient determination which involves only integrals of the profile.

The results of applying this approximation to two-dimensional (wide channel) flow conditions are presented in a curve fit form suitable for computer computations (lines 5090 through 5320 of appendix B, section 7) as:

$$c = 1+\exp\left\{ \{a_{4,3}\ \ell n(S) + \sum_{i=0}^{3} a_{i,3}\ C_I^{i}\}\ \ell n(X) + \sum_{j=0}^{2} \{a_{4,j}\ \ell n(S) + \sum_{i=0}^{3} a_{i,j}\ C_I^{i}\}\ X^{j} \right\} \quad (1.8)$$

where c is the coefficient (either α or β), and X maps the interval of equation 1.2a onto the interval [0,1] through the relation:

$$X = \frac{\ell n(q) - \ell n(0.0025\ C_I^{2.5})}{\ell n(36) - \ell n(0.0025\ C_I^{2.5})} \quad (1.9)$$

where q is the volumetric discharge per unit width in cubic feet per second per foot. The required coefficient matrices are presented in tables 1.1 and 1.2. The curve fit relations are applicable for values of X between 0 and 1, slopes from 0.001 to 0.20, and curve index values greater than 2.0.

For channels where the two-dimensional flow assumption is not acceptable, reference values of the coefficients are determined by assuming two-dimensional flow in a channel having a flow depth equal to the maximum depth in the actual cross section. The energy coefficient is then found by multiplying the reference value by the three-fourths power of the ratio of the mean velocity which would exist for the two-dimensional channel to the actual computed mean velocity (for example application, see appendix B, section 7, lines 4830 through 5010). The adjustment factor for the momentum coefficient is the one-third power of the same ratio. Although these relations were found to agree well with the available data and represent the best approximations available, the simplifying assumptions required for their development should be recognized.

STABILITY LIMITS

In this discussion, it is assumed that the grass channel lining is used to protect an erodible soil boundary. Given this assumption, the stability limits of concern are those related to the prevention of channel degradation. Since significant bed load transport with its associated detachment and redeposition is incompatible with the maintenance of a quality grass cover, consideration may be further limited to particle or aggregate detachment processes. This limitation results in the logical dominant parameter being the boundary stress effective in generating a tractive force on detachable particles or aggregates.

For the soils most often encountered in practice, particle detachment begins at levels of total stress low enough to be withstood by the vegetation without significant damage to the individual vegetal elements. When this occurs, the vegetation is undercut and the weaker vegetation is removed. This removal decreases the density and uniformity of the cover, which in turn leads to greater stresses at the soil-water interface, resulting in an increased erosion rate. The progressively increasing erosion rate leading to unraveling of the lining is accentuated in supercritical flow by the tendency for slight boundary or cover discontinuities to cause flow and stress concentrations to develop.

For very erosion-resistant soils, the vegetal elements may sustain damage before the effective stress at the soil-water interface becomes large enough to detach soil particles or aggregates. Although the limiting condition in this case is the stress on the vegetal elements, failure progresses in much the same fashion. Damage to the vegetal cover results in an increase in effective stress on the soil boundary until conditions critical to erosion are exceeded. The ensuing erosion further weakens the cover, and unraveling occurs.

The potential for rapid unraveling of a channel lining once a weak point has developed, combined with the variability of vegetative covers, forces design criteria to be conservative. Very dense and uniform covers may withstand stresses substantially larger than those specified herein for short periods without significant damage. Reducing of the stability limits is not advised, however, unless a high level of maintenance guarantees that an unusually dense uniform cover will always exist. Also, unusually poor maintenance practices or nonuniform boundary conditions should be reflected in the design. (See chapter 3 for further discussions related to parameter estimation.)

Effective Soil Stress

The boundary stress effective in the detachment of soil particles is that associated with viscous drag on the soil boundary and pressure drag on soil particles or aggregates of a size that may be individually moved by the flow. Although it is convenient to think of this stress in terms of a time- and space-averaged stress associated with soil grain roughness, the temporal and spatial distribution of the stress is also important and is influenced directly by the presence of the vegetation. The computed erosionally effective boundary stress must, therefore, include consideration of this action.

Since Einstein (1950) introduced his sediment transport model that included a separation of form and grain roughness, numerous models and assumptions have been proposed for the separation of boundary stresses into components. Because of the complexity of the processes involved, none of the proposed approaches are analytically complete or exact. An approach that has proved effective for use in both nonvegetated (Taylor and Brooks 1962) and vegetated channels (Temple 1980) is to assume that, for a given discharge, the energy loss associated with a given component boundary roughness is an invariant function of the hydraulic radius. Under this assumption, the energy slope is divided into components as:

$$S = S'+S''+S''' \tag{1.10}$$

where S' = the energy slope associated with the soil grain roughness,
S'' = the energy slope associated with boundary form roughness, and
S'''= the energy slope associated with the vegetal roughness or drag.

With the component roughnesses assumed to be expressed in terms of Manning's coefficients for each, and Manning's equation assumed to apply for each component, the total roughness is computed as the square root of the sum of the squares of the components (eq. 1.4). These same assumptions lead to S' being defined in terms of the component roughnesses as:

$$S' = S\ (n_s/n)^2 \tag{1.11}$$

Accounting for the fact that energy lost to the flow represents work done by a force acting on the moving water, the stress component separation is given by:

$$\tau = \gamma RS = \gamma RS'+\gamma RS''+\gamma RS''' \tag{1.12}$$

in which τ is the gross mean boundary stress, γ is the unit weight of water, and the term involving S' is the mean boundary stress associated with the soil grain roughness. With n_s

considered to be a known property of the soil, the mean boundary stress associated with the soil may be computed.

The effect of the vegetation on the spatial and temporal distribution of the boundary stress is more difficult to determine on the basis of physical principles. Observations of flow behavior indicate that the characteristics of the cover most important in preventing local and/or temporary high stresses on the soil boundary are the cover density and, probably more important, uniformity of density in the immediate vicinity of the boundary. Since no adequate means is available for expressing these characteristics in terms of measurable parameters, Temple (1980) introduced an empirical vegetal cover factor for use in tractive stress design of grass-lined channels. Using this factor, the [erosionally] effective boundary stress for use in design is computed by the relation:

$$\tau_e = \gamma DS(1-C_F)(n_s/n)^2 \qquad (1.13)$$

in which τ_e = the effective stress on the soil,
D = the maximum flow depth in the cross section,
C_F = the vegetal cover factor,

and the other variables are as previously defined. Examination of this relation shows the possible range of the cover factor to be between 0 and 1, where a value of 0 would imply no vegetal protection and a value of 1 would imply complete isolation of the soil boundary from stresses generated by the flow. Calibration of the cover factor using available vegetated channel stability test data resulted in a 0.5 to 0.9 range for the covers tested. For the relatively dense uniform covers tested, variations in cover density and uniformity of density are dominated by vegetal growth characteristics. Therefore, the cover factor is presented as a tabular function of vegetation type (table 3.1). Since this type of a tabular function cannot account for variations in maintenance practice and stand quality, judgment is required in the selection of this factor for a particular design.

The flow depth rather than the hydraulic radius is used in equation 1.13 because it is the maximum, rather than the average, stress which will initiate failure. The boundary stress correction factors suggested by Lane (1955) and reproduced by the SCS (1977) and others could probably be applied to the effective stress computed by equation 1.13 without significant error. The more conservative approach of ignoring this correction is advised, however, because of the distortion of the stress distribution that will result from the interaction of the vegetation with the flow and because of the tendency for a vegetative lining to unravel once damage has been initiated.

Allowable Effective Soil Stress

By definition, the allowable soil stress is the same for vegetated channels as for those unlined channels for which effective stress or tractive force is a suitable design parameter. For effective stress to be applicable as the sole stability parameter, detachment rather than sediment transport processes must dominate stability considerations. This means that sediment deposition and sediment transport as bed load must be negligible. As pointed out by Patronsky and Temple (1983), this is essentially the same restriction as must be applied to grass-lined channels if a quality cover is to be maintained.

Lane (1955) developed the tractive force approach for channel design in relatively coarse materials where stability usually implies satisfaction of the above restrictions and introduced the relation:

$$\tau_a = 0.4\ d_{75} \qquad (1.14)$$

when:

$d_{75} > 0.25$ inch

where τ_a is the allowable stress in pounds per square foot, and d_{75} is the particle diameter in inches for which 75 percent of the material is finer. The Soil Conservation Service (SCS) (SCS 1977) uses this equation for the design of unlined channels in coarse noncohesive materials. The SCS procedure uses equation 1.13 ($C_F = 0$ for an unlined channel) to compute the effective stress, with the soil grain roughness determined by the relation (Lane 1955):

$$n_s = \frac{d_{75}^{1/6}}{39} \qquad (1.15)$$

where d_{75} is again given in inches.

For fine-grained materials, application of tractive force or effective stress concepts to unlined channels is less straightforward because of the need to consider sediment transport and bed load particle redeposition processes. Attempts to use allowable stress or velocity as the primary design parameter have usually led to limiting conditions which are dependent on the sediment concentration in the flow as determined by sediment transport capacity and sediment supply considerations. The previously introduced bed-load limitation for vegetated channels means that the comparable condition for grass-lined and unlined channels is that specified as clear water or sediment free. This restriction also means that the bed forms normally present in unlined channels in fine noncohesive materials will not form in vegetated channels. Therefore, design limits dependent on their presence are not applicable to vegetated channels.

SCS (1977) presents both a permissible velocity and an allowable stress procedure applicable to the design of unlined channels in fine noncohesive material. The allowable stress procedure uses the mean particle diameter (d_{50}) as the variable determining allowable stress. The effective or "actual" stress is determined using a modification of Einstein's (1950) approach. Although the clear water allowable stresses appear reasonable for use with the grass-lined channel design procedure, the approach, as used by SCS, implies the presence of well-defined bed forms, making comparison to zero bed-load conditions questionable. Also, the use of d_{50} rather than d_{75} makes comparison of the fine-material allowable stress curves with equation 1.14 difficult.

The permissible velocity procedure is used for both cohesive and noncohesive fine-grained material. d_{75} is used as the primary soil parameter for noncohesive material, and the means of determining flow resistance is not specified. Since d_{75} is the same parameter used to determine the allowable effective stress for coarse material, the design limits may be directly compared by assuming a reference channel geometry and assuming equations 1.13 and 1.15 to apply to channels constructed in fine material. The results of such a comparison are shown in figure 1.2. Two reference channel geometries were used in the construction of this figure. The first was the conservative assumption of a straight wide channel (hydraulic radius equal to flow depth) having a flow depth of 3 ft. This assumption leads to a conversion relation given by:

$$\tau_a = 19.6\ V_a^2 n_s^2 \qquad (1.16)$$

where V_a is the permissible velocity and the other variables are as previously defined. The second is the less conservative channel geometry assumed by Lane (1955). Lane's stress distribution factors were also considered to apply in the construction of this curve. For the reasons previously discussed, only the permissible velocities applicable to "sediment-free" flows are shown in figure 1.2.

Examination of figure 1.2 in light of the variability of the parameters required for stable channel design suggests that for the bed-load limited condition applicable to grass-lined channels, equations 1.14 and 1.15 may be used for noncohesive material with grain sizes (d_{75}) greater than 0.05 inch. For grain sizes less than 0.05 inch, the soil grains are considered to be effectively submerged in the viscous sublayer of the flow with the grain roughness and allowable effective stress both considered to remain constant at limiting values of n_s=0.0156 and τ_a=0.02 lb/ft^2.

Possibly because of the variability of material properties and the complexities of the interaction of the flow with boundary sediments in the form of bed material transport, allowable stress has not been widely used for the design of channels in cohesive materials. The SCS (1977) offers only a permissible velocity procedure for stability design of channels in cohesive materials. The soil parameters used to determine the permissible velocity are the soil's classification in the unified soil classification system, its plasticity index, and its void ratio. In applying the procedure, a basic permissible velocity is first obtained from the soil's classification and its plasticity index. This basic velocity for the material is then multiplied by a correction factor that is a function of soil classification and void ratio.

In converting the SCS (1977) criteria to an effective stress format, it is convenient to convert the basic velocities directly using equation 1.16[3] and adjust the resulting allowable stress by the square of the void ratio correction factor used by SCS. Since n_s is by definition the soil grain roughness associated with particles or aggregates of a size capable of being detached by the flow, equation 1.16 may be applied with an n_s value of 0.0156 to convert these permissible velocities to values of allowable effective stress if it is assumed that erosion of these materials is primarily through detachment of particles or aggregates with diameters less than 0.05 inch. The effective stresses equivalent to the SCS (1977) permissible velocities obtained for cohesive materials using this approach are presented in both graphical and numerical formats in chapter 3 (tables 3.3, figures 3.1 through 3.4). With the limiting conditions expressed in this fashion, the design procedure for grass-lined channels is independent of soil type, providing the

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[3]The selection of the more conservative channel geometry leading to equation 1.16 is considered to be in line with the high degree of uncertainty involved in determining the erodibility of cohesive soils.

vegetal limitations are observed. The procedure is also applicable to the design of unlined channels for which the zero bed-load transport limitation is reasonable.

Limiting Vegetal Stress

Because the failure most often observed in the field and in the laboratory has resulted from the weakening of the vegetal lining by removal of soil through the lining, few data exist related to the maximum stresses that vegetal elements rooted in highly erosion-resistant materials may withstand. Observations of cover damage under high stress conditions (Ree and Palmer 1949), however, indicate that this type of failure may become dominant when the vegetation is established on highly erosion-resistant soils. These observations also indicate that when vegetal failure occurs, it is a complex process involving removing young and weak plants, shredding and tearing of leaves, and fatigue weakening of stems. The complexity of this process combined with limited data force the stability limitation developed below to be only a rough approximation. A more detailed treatment would require the inclusion of many additional variables, not normally available in the design situation, to adequately describe both the soil and the cover. The use of an approximating relation, therefore, is considered appropriate for most practical applications.

For conditions where the soil surface remains intact, the dominant action associated with vegetal cover failure appears to be fatigue-related stem breakage combined with leaf damage and removal. Force is transmitted from the flow to a vegetated boundary by drag along the entire length of a submerged vegetal element. This distribution of force along the stem, coupled with the fact that the waving action of longer stems will be at a lower frequency, and with the increased size and maturity [usually] associated with greater stem length, suggests that the allowable boundary stress associated with the vegetation should increase with stem length and density. An approach consistent with these considerations and with the limited data available on vegetal failure is to assume that the allowable vegetal stress is directly proportional to the retardance curve index. Using the available data to estimate the proportionality constant results in:

$$\tau_{va} = 0.75\ C_I \tag{1.17}$$

in which τ_{va} is the maximum allowable stress on the vegetation in pounds per square feet and C_I is the previously defined retardance curve index.

To be consistent with the discussion in the previous section, the vegetal stress, τ_v, for a given flow condition would be computed as the gross boundary stress adjusted by the square of the ratio of the vegetal roughness coefficient to the total roughness coefficient. Because of the limited data available, the usual dominance of vegetal resistance, and the simplifying assumptions required for vegetal roughness computation, equation 1.17 was developed under the assumption that:

$$\tau_v = \tau - \tau_e \qquad (1.18)$$

This approach is more computationally convenient in that no new parameters are required for the vegetal stability check.

ADDITIONAL CONSIDERATIONS

The relations discussed previously are those which are necessary for any grass-lined channel stability design application and/or are unique to the use of grass as a channel lining. For clarity of presentation, the relations are generally developed in the context of steady uniform flow in a prismatic channel. Therefore, this presentation cannot be used as the sole reference for all design problems involving grass-lined channels. An attractive point of the effective stress approach to design, however, is that such problems as Froude number, water surface stability checks, and curvature super elevation computations, may be handled using the same procedures for both lined and unlined channels.

Although the same relations are used for both lined and unlined channels, engineering judgment remains an essential part of the design process, and certain cautions must be observed. Most relations used in open channel design are based on the conservation of mass, energy, and/or momentum. In many instances, the most familiar form of a relation is one that has been simplified by the assumption of momentum and energy coefficients equal to unity. Because this is not always an acceptable assumption for a grass-lined channel, however, the familiar procedures or relations should be re-examined and the appropriate coefficients included prior to their application to conditions involving grass linings.

Engineering judgment is also essential to determine the influence of maintenance practices on design parameters. For example, regular mowing of a turfgrass cover over a well-prepared soil bed may significantly increase vegetal density and uniformity, resulting in an increased value of the vegetal cover factor appropriate for the lining. Conversely, untimely cover removal from a soil surface containing significant discontinuities may leave the soil more open to local erosive attack.

Under supercritical flow conditions, relatively minor discontinuities in flow resistance and/or elevation may cause significant flow and stress concentrations. And extreme discontinuities such as animal or vehicular trails paralleling the flow may negate the protective benefits of the vegetal lining. Appropriate care should therefore be exercised in the development of maintenance programs for this type of channel.

Table 1.1
Curve fit coefficient matrix for use in the computation of the energy coefficient α

i \ j	0	1	2	3
0	4.31	-9.19	1.99	1.57
1	.230	-.0216	.178	-.000932
2	-.0177	.00857	.00159	.00364
3	.000155	.000815	-.00114	-.000283
4	.0298	.0833	.00796	-.000359

Table 1.2
Curve fit coefficient matrix for use in the computation of the momentum coefficient β

i \ j	0	1	2	3
0	2.93	-7.68	0.800	1.54
1	.0888	.152	.223	-.035
2	-.0000729	-.0220	.00518	.00845
3	-.000669	.00226	-.00146	-.00053
4	.0146	.0828	.0263	-.00304

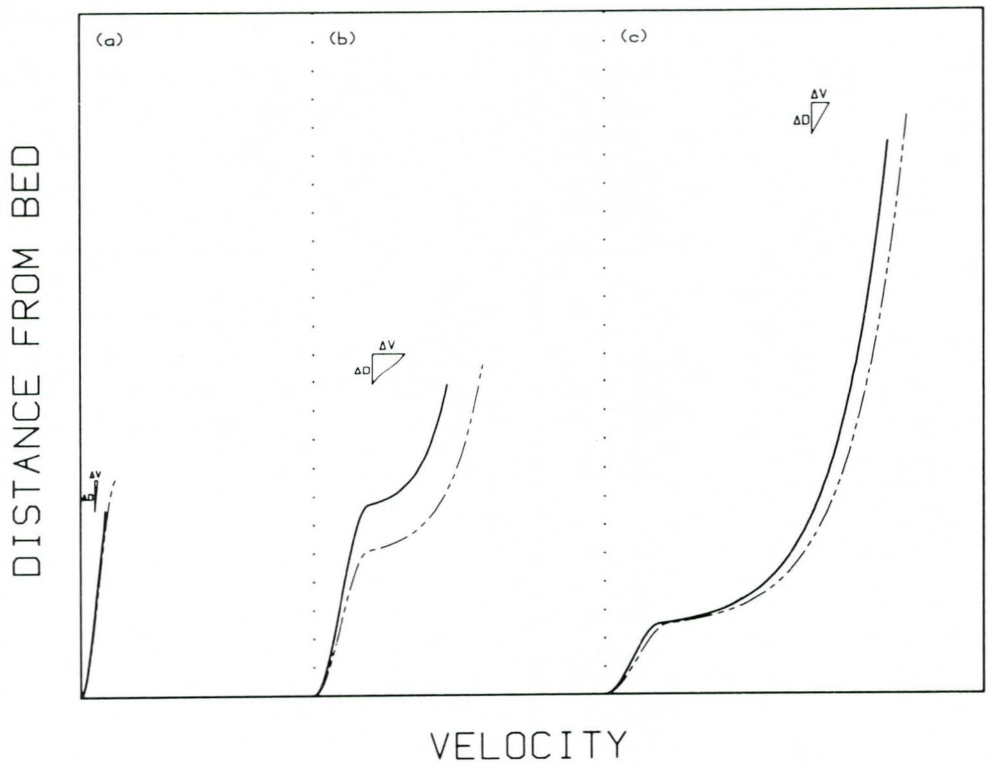


Figure 1.1
Velocity profile sketch illustrating the effect of an increase in flow depth on velocity in (a) the low-flow region, (b) the intermediate-flow region, and (c) the high-flow region.

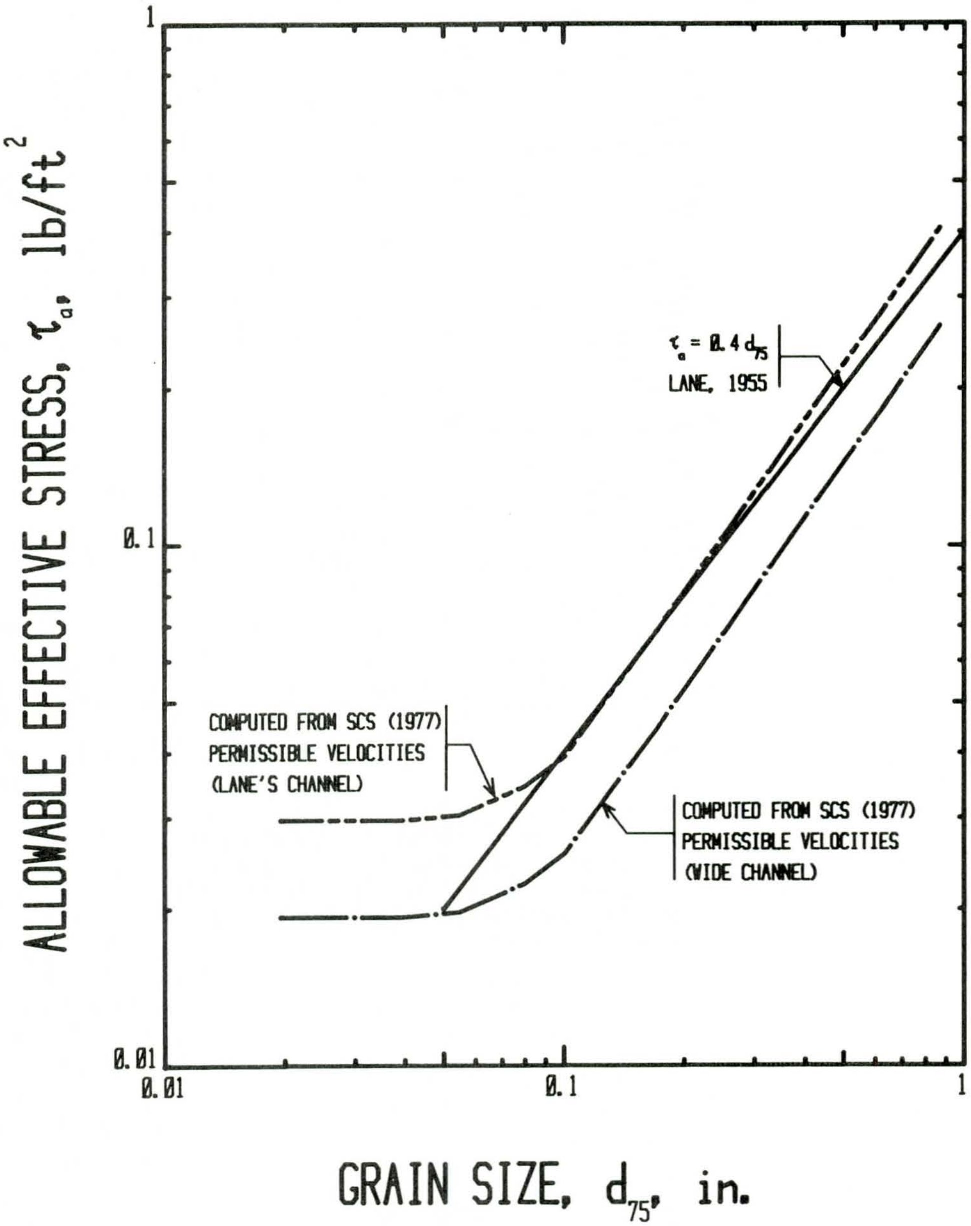


Figure 1.2
Comparison of Lane's (1955) allowable stress stability criteria with the SCS (1977) criteria for sediment-free flow over the same material

2. SPECIES SELECTION, ESTABLISHMENT, AND MAINTENANCE OF GRASS-LINED CHANNELS

By R.M. Ahring and A.G. Davis

The selection of grass species for use in waterways (channels) for erosion control is based on site-specific factors: (1) Soil texture, (2) depth of underlying material, (3) management requirements of vegetation, (4) climate, (5) slope, and (6) type of structure or engineering design. Expected flow rate (Ree and Palmer 1949), availability of seed, ease of stand establishment (germination and seedling growth habit), species or vegetative growth habit, plant cover (aerial parts, height, and mulch), and persistence of established species are other factors that must be considered in selecting the appropriate grass to meet conditions critical to channel stability.

Soil and climate of a particular area determine the best adapted grass species for erosion control in lined channels. The soils of an area in part determine the vegetal association in that:

1) Sandy soils take water rapidly, but do not retain moisture as long as finer textured soils.
2) Moisture is more readily caught, stored, and returned to plants grown on sandy soils.
3) Fine-textured soils are more slowly permeable than sandy soils and are characterized by (a) greater runoff, yet are less erodible; (b) less total storage capacity because of well-developed B horizons; and (c) lower yield of water to plants due to the higher colloidal fraction.

Channel construction should be sequenced to allow establishment of the grass stand before subjecting the channel to flow other than local runoff. This is often possible when the grass-lined channel(s) is built in conjunction with hydraulic structures such as reservoirs or terraces. Completed structures need a quick and uniform cover of vegetation for soil stabilization and erosion control. Establishing permanent covers must be tailored for each location because channel stability is a site-specific problem until vegetation is well established. Establishment involves liming and fertilizing, seed bed preparation, appropriate planting dates, seeding rates, mulching, and plant-soil relationships. These activities must be properly planned, with strict attention to rainfall patterns. Often the channel is completed too late to establish permanent grasses that grow best during the optimum planting and establishment season.

SELECTING PLANT MATERIALS FOR ESTABLISHING TEMPORARY CHANNEL COVERS

Channels are often exposed from a few weeks to 9 months (Ree, 1949) to wind and water erosion unless protected by a temporary ground cover. Based on flow tests on sandy clay channels, Ree et al. (1977) suggested the use of wheat (*Triticum aestivum* L.) for winter and sudangrass [*Sorghum sudanensis* (Piper) Hitchc.] for late-summer temporary covers. These temporary covers increased the permissible discharge rate to five times that of an unprotected spillway. Other annual and short-lived perennials used for temporary seedings include (1) barley (*Hordeum vulgare* L.), noted for its early fall growth; (2) oats (*Avena sativa* L.), in areas of mild winters; (3) mixtures of wheat, oats, barley, and rye (*Secale cereale* L.); (4) field bromegrass (*Bromus* spp.); and (5) ryegrasses (*Lolium* spp.). Summer annuals, for example, German and foxtail millets (*Setaria* spp.), pearl millet [*Pennisetum americanum* (L.) Leeke], and certain cultivated sorghums other than sudangrass (Atkins 1957; Vallentine 1971), may also be useful for temporary mid- to late-summer covers. Since millets do not continue to grow as aggressively as sorghums after mowing, they may leave a more desirable, uniformly thin mulch for the permanent seeding. Temporary seedings involve minimal cultural treatment, short-lived but quick germinating species, and little or no maintenance. The summer covers should be close-drilled stands and not be allowed to seed. The protective cover should provide stalks, roots, and litter into which grass seeds can be drilled the following spring or fall.

Many grasses can be used for vegetal channel linings (Allred and Nixon 1955; Atkins and Smith 1967; Hafenrichter et al. 1949, 1968; Schwendiman and Hawk 1978). The most preferred warm- and cool-season grasses for waterway channels are the tight-sod-forming grasses; that is, bermudagrass [Cynodon dactylon var dactylon (L.) Pers.], bahiagrass (Paspalum notatum Flugge), buffalograss [Buchloe dactyloides (Nutt.) Engelm.], intermediate wheatgrass [Agropyron intermedium (Host) Beauv.], Kentucky bluegrass (Poa pratensis L.), reed canarygrass (Phalaris arundinacea L.), smooth bromegrass, (Bromus inermis Leyss.), vine mesquitegrass (Panicum obtusum H.B.K.), and Western wheatgrass (Agropyron smithii Rydb.). These grasses are among the most widely used species and grow well on a variety of soils.

To understand the relation between different grasses and grass mixtures to grass-lined channel use value, one must consider growth characteristics and grass-climate compatibilities in the different geographic areas of the United States. A grass mixture should include species adapted to the full range of soil moisture conditions on the channel side slopes. Table 2.1 is intended primarily to show some of the different kinds of grasses used in grass-lined channels. Conservationists and agronomists of each State should know the best soil-binding grass species adapted to their particular areas, seeding rates, dates of seeding particular grass species, and cultural requirements for early maximum cover. The most important characteristic of the grass(es) selected is its ability to survive and thrive in the channel.

The list of grasses and characteristic growth habits is not complete, and many more species could be added. It is important, however, to know the origin, range of adaptation, and growth habits of the grass strains in conservation work. Grass breeding and selection have resulted in the release of several varieties of a particular grass species. Some varieties may be better adapted to specific areas and site situations, thus requiring less time to become established than others. Bermudagrass is probably the most widely used in the South. It will grow on many soil types, but at times it may demand extra management. It forms a dense sod that persists if managed properly.

When bermudagrass is used, winter-hardy cultivars should be obtained. Improved cultivars, such as 'Coastal' (Burton 1948), 'Midland' (Harlan et al. 1954), 'Greenfield' (Elder 1955), 'Tifton' (Burton and Monson 1978), and 'Hardie' (Taliaferro and Richardson 1980), do not produce seed, and must be established by sprigging. Where winters are mild, channels can be established quickly with seed of 'Arizona Common.' Seed of 'Guymon' bermudagrass, a new seed-propagated variety with greater winterhardiness than 'Arizona Common,' was jointly released in 1982 by the USDA-ARS and the Oklahoma Agricultural Experiment Station (Ahring et al. 1982) and should be available commercially within a few years. Bermudagrass is not shade tolerant and should not be used in mixtures containing tall grasses. However, the inclusion of winter annual legumes such as hairy vetch (*Vicia villosa* Roth.), narrowleaf vetch [*V. sativa* L. subspecies *nigra* (L.) Ehrh.] (Ball 1968), and/or a summer annual such as Korean lespedeza (*Lespedeza stipulacea* Maxim.) may be beneficial to stand maintenance.

The selection of species used in channel establishment often depends on availability of seed or plant material. Chronic national seed shortages of some warm-season grasses, especially seed of native species, have often led to planting seed marginally suited to site situations. Lack of available seed of desired grass species and cultivars adapted to specific problem sites is a major constraint often delaying or frustrating seeding programs. In addition to the grass species or base mixture of grasses used for erosion control, carefully selected special-use plants may be added for a specific purpose or situation. Desirable wildlife food plants may be included in the mixture if they do not compete to the detriment of the base grass(es) used for erosion control. Locally adapted legumes are often added if they are compatible with the grass(es) and noncompetitive.

On large watershed projects, the problems of seed supply should be resolved before a project is started. Special "seed" increase funds may be needed to avoid bottlenecks later in the program. Such funds could be used to contract the production of needed quantities of specific grass seeds over a projected period of time.

Removing topsoil from channel sites before excavating and returning it to the excavated channel is frequently the determining factor in establishing a good uniform grass cover. Usually, it is necessary to save and replace topsoil over the exposed channels. For some channels, however, the subsoil of channel beds, when fertilized, could be an adequate medium for establishing grass. We have no fast rule for determining the depth of topsoil to place over exposed channels other than that topsoil and depth of suitable subsoil should be at least 18 inches for good plant growth and root concentration of seeded grasses. At least 6 to 10 inches of topsoil must be added to establish grass in channels cut in coarse-textured/low-fertility soils. Channel fertilization needs should be based on soil test results, and when needed, fertilizer should be applied at the time of planting, after the topsoil is replaced.

Where channels are excavated into clay subsoils, 12 inches or more of good topsoil should be added back and worked into the top 6 inches of the channel bed and side slopes. Topsoil replacement should be staked for proper depth to make use of available soil quantities. Tillage measures should be taken to limit slippage at contact layers and to promote plant root penetration and water infiltration. Grass species that have high tolerance for soluble salts and exchangeable sodium should be established on channels cut in highly saline and alkali soils.

To expedite control of erosion and sediment, seedings must be made almost concurrently with channel excavation. When moisture conditions are not favorable and irrigation is practical, short supplemental irrigations may be used to hasten the growth of a suitable cover. Permanent seeding should be timed to obtain the maximum establishment before exposure to flows.

The technology, equipment, and plant species used in other areas, for example, roadside stabilization (Environmental Protection Agency 1975) and land rehabilitation (Cook et al. 1974; McKell et al. 1979; Robbins 1980; Schuman and Power 1980), are applicable to the stabilization of grass-lined open channels.

Preplanting Considerations

Before planting, a soil test should be made to test soil pH and insure that nutrients, especially nitrogen, phosphorus, and potassium levels, are adequate.

A firm, weed-free seedbed, with just enough loose surface soil for uniform depth of cover, is essential. Such a seedbed is important in obtaining uniform planting depths and improving seed-soil contact. Seed planted in loose soil is usually planted too deep, and seedlings fail to emerge; or seeds may germinate following a light rain but die after the soil dries out before seedlings can develop sufficient roots for establishment.

Soil temperature (65 to 86°F for warm-season grasses and 60 to 86°F for cool-season grasses) and moisture must be favorable. Time of seeding should be based on whether species are classified as cool- (fall-sown) or warm-season (spring-sown) grasses.

Planting dates should be selected to avoid expected periods of critical weather, such as heavy rainfall and runoff, and extended dry periods.

Select adapted species or a combination of adapted grass species which will withstand the degree of inundation expected, establish themselves rapidly from seeds or sprigs, and compete well with weeds. Also, consider the possible use of certain preemergence herbicides to control weeds during establishment (Huffine et al. 1982; Kay 1971; McMurphy 1969; Smith 1983).

Where severe weed problems are anticipated, spraying activated carbon (20 to 27 lb/acre) slurries (Lee 1973, 1978; Rolston et al. 1979) in narrow bands on the soil surface of each seed row at the time of planting, followed by a broadcast application of nonselective herbicide(s), may be a useful technique. The activated carbon absorbs and inactivates the herbicide, giving a narrow band of protection above the seed zone.

Seed Germination

Uniform seed germination is essential to producing a uniform cover over the entire site. Germination can be enhanced by consistency and attention to contributing factors.

Seed should not be planted deeper than 0.25 inch (heavy soils) to 0.75 inch (light soils). Small discrepancies in depth of planting in heavy soils can be disastrous. Special grass drills with depth band openers are available to get proper planting depths.

Planting dates should be timed to favorable moisture and soil temperatures conducive to germination and seedling establishment.

A seeding rate should be selected to give the desired number of plants per unit area. Uniformity of established cover is essential to prevent flow and boundary stress concentration within the channel. Mixtures require a higher seeding rate than does a planting of a single species. The SCS specifications for critical area seedings recommend one and one-half to two times the normal seeding rate. However, where a vegetative cover is urgently needed, seeding rates of mixtures probably should include enough seed to obtain a stand of each species alone in the event conditions are not favorable for germination and emergence of one or another species in the mix. Although mixtures may be more effective on certain sites in reducing erosion and resisting weed encroachment, mixed plantings should be kept simple (Decker et al. 1978; Huffine et al. 1982). No more than two or three species in a mixed planting is preferred. The mixture seeded should be solely for erosion control. Dual-purpose seedings tend to weaken the required surface protection and cause conflicts in maintenance.

Where temporary channel covers are established the year before and mowed before seed is formed, it may be necessary to cultipack the area before planting in the spring. During late fall or early spring, cool- and/or warm-season grasses can be drilled into the undisturbed mulched firm seedbed.

Where winter annuals have been used to stabilize channels, herbicides can be used to kill the stand early before growth is too heavy. The herbicide application should also eliminate winter weeds. Direct seed the warm-season grass(es) without removing any of the mulch litter. The seedbed beneath the mulch should be firm. Whenever planting is done on littered or mulched seedbed, use special grass drills with double coulter openers to cut through the mulch.

Stand Failure

Stand failures can be attributed to any one, or combination, of several factors. Seedling growth after emergence may be affected by undesirable soil pH, low soil fertility, improper use of preemergence and postemergence herbicides, or soil compaction by heavy machinery. Other causes of stand failure are--

1) Use of seed that has a high percentage of firm (dormant) seeds can result in slow germination, permitting the weed seeds to germinate and emerge well ahead of the intended grasses.

2) Lack of chemical or mechanical weed control can cause poor seedling establishment, since weeds compete with grass seedlings for soil moisture, nutrients, and light.

3) Failure to protect a channel from concentrated runoff following a storm, or crusted soil surfaces resulting from heavy rains after planting, can prevent emergence of grass seedlings, especially on fine-textured soils.

4) High wind velocities and movement of sand particles can be a hazard to stand establishment, especially on coarse-textured soils.

5) Winter-kill because of late planting in the fall, late emergence of an earlier planting, or planting nonadapted grass cultivars can result in stand failures.

6) High temperatures on soil surfaces and drought probably are the most common causes of stand failure.

The critical need for grass-lined channel structures is a vegetative cover of uniform density and height (McCool 1970; Temple 1982) at the time of flow. Success in stabilizing water channels requires a great deal of skill. In some channels, a quick establishment of cover is required. In others (notably spillways and floodways), proper planning can allow adequate time for establishing cover.

Methods of Establishment

Grass seeds are small, often chaffy, and difficult to plant without special equipment. Several planting methods follow.

The drilling method of planting seed using a depth band grass drill is recommended in channels where seedbed preparations are smooth. Drills utilize the available seed more efficiently, place the seed more accurately, and increase the probability of establishment success. In drill planting, rows paralleling the channel flow should be avoided, and close row spacings should be used to maximize uniformity of cover. Rough seedbeds hold more water and reduce the chances of wind damage better than smooth seedbeds. However, rough, cloddy seedbeds require a higher seeding rate because planting depths (soil covering) and soil-seed contact are not uniform. Usually only a small fraction of the viable seed planted on such seedbeds produce surviving seedlings. A wide selection of grass seed drills are available (Larson 1980). Most feature double or single-disk furrow openers, with and without depth-band gauges attached to the disks, and heavy-duty press wheels or drag devices to cover the seed. Hoppers are similar to conventional drills with the addition of various agitators and feed mechanisms for planting chaffy seed.

The broadcast method involves spreading seed over the area intended for establishment followed by a cultipacker or drags to ensure the seeds are covered with a uniform layer of firm soil. Types of broadcast planters used vary from tractor-mounted rotary spreaders to Brillion® seeders. As a rule, broadcast planting requires about twice as much seed to obtain a uniform stand as does drilling.

Sprigging, sodding, and mulch sodding are common methods of establishing bermudagrass. The minimal rate for establishing channels to bermudagrass is 40 bu/acre equivalent of viable sprigs (rhizomes and stoloniferous plant material). Sprigging rates required vary with quality of sprigs and time of year. Planting equipment (sprigger) should be operated at about 4 mph and adjusted to plant sprigs uniformly at 3 to 4 inches deep in 18- to 24-inch rows. After planting, the channel should be compacted and watered.

In sodding, a well-developed sod (source) is cut 10 to 12 inches wide and 3 inches thick and laid tightly in rows at right angles to the slope. Sod-slab joints are staggered from one row to the next. All openings in the laid sod and joints are filled with friable soil, and the area is rolled or tamped for firm sod-soil contact. A tiedown wire (poultry wire) is often used to hold sod in place and prevent erosion until roots tie soil layers together. Structures sodded are usually watered to stimulate sod recovery.

For mulch sodding, the sod source is thoroughly cut up and mixed to a 4- to 8-inch depth by disking in two directions. This 4 to 8 inches of topsoil and chopped sod material (mulched sod) is then removed and dumped on the roughly tilled (4-inch depth) site and spread to a thickness of at least 4 inches. Following compaction, the mulch channel should be watered (3 to 4 gal/yd^2).

Hydroseeding and mulching provide a method of planting on moderate to steep slopes, but require large amounts of water (Huffine et al. 1982; Young, et al. 1977). Hydroseeding should be followed by mulching as a separate operation. Mulches include:

1) Long-stem wheat straw (preferred), clean prairie hay, and so forth. Straw or hay mulches are either broadcast and "punched" in (4-5 inches deep) on moderate slopes with a straight disk, or broadcast along with an adhesive or tacking agent (that is, asphalt emulsion) on steep slopes. About 1.0 to 1.5 tons/acre of straw is ideal. Mulches conserve surface moisture and reduce summer soil surface temperatures and crusting. The disadvantages of hay and straw mulches are that they can be a source of weed seed, and too much surface mulch, regardless of kind, can cause seedling disease problems, for example, "damping-off." Commercial wood fiber mulch materials are available for relatively level areas.

2) Soil retention blankets or mats made of various interlocking fabrics and plastic webbing can be used on extremely steep slopes in areas with a high potential for water movement. These tiedown erosion blankets prevent seeds from being washed out by rain, and at the same time mulch and enhance germination and establishment.

New methods of establishing grasses that may have future merit for grass-lined channels are the "fluid" drill and the "Automatic Bandoleer" seedling transplant methods.

The fluid drill method involves planting partially germinated seedlings (root-radicle exposed) suspended in carrier "gels" (starch base). By means of peristaltic pumps, the gel containing partially germinated seeds is extruded into the seedbed immediately behind coulters. The drills will sow controlled beads of gel with a consistent number of partially germinated or primed seeds per length of row.

With the Automatic Bandoleer transplanting method (Hauser 1981), plants are grown from seed under greenhouse conditions in bandoleers, or growing trays, for machine planting. The transplant machine pushes plugs with growing seedlings into furrows and firms the soil around the plant.

Advantages of both methods are (1) uniform planting density, (2) a rapid and predictable emergence of seedling and transplant survivability, (3) reduced susceptibility to environmental stresses and uncertainty of obtaining suitable stands from seed, and (4) reduction of poor seedbed quality or preparation as a detriment to stand establishment. The disadvantage is the initial cost of the methods.

Manmade grass-lined channels encompass diverse soil types, climate-vegetal associations, and topography. Management plans with stated goals and objectives are necessary to maintain and direct water flow drainage and prevent damage to channel structures. Grass-lined channels should be inspected after heavy rains and in the spring after the snow melts so that potential problem sites can be detected and repaired. Inspections should be made at regular intervals on foot. If vehicles must be used, the route taken should never be used twice in the same season because of track damage and the danger of track erosion.

Undesirable weedy plants often invade channels, especially on channel side slopes, and create problems of water flow (Gwinn and Ree 1980) by impeding or redirecting water movement. If allowed to persist and spread, these undesirable plants can cause severe erosion damage to the channel.

Weeds

Three categories of weeds are (1) grasses, (2) broadleaf, and (3) woody. The first step in weed control and management is to find the cause of the weed infestation. Weed control (killing) without correcting the basic cause of the problem will give only temporary relief, will not regenerate the established stand, and will increase costs of channel maintenance over time. Weed control may result in substantial discontinuities in density of cover and cause boundary stress concentrations that lead to an unravelling of the channel through gullying and undercutting of the vegetal cover. Burrowing rodents also can cause similar problems. Use of nitrogen fertilizers may stimulate the self-healing capability of some of these covers.

Causes of weed infestation include:

1) Failure to control weeds in early stages of infestation.

2) Establishment of grass species not well adapted to either climate and/or soil conditions of a particular area.

3) Poor soil fertility--some grasses may become sod-bound (nitrogen deficient) or unproductive due to plant nutrient deficiencies other than nitrogen.

4) Competitive nature of weeds--severe winter and dry spring weather may delay spring emergence and growth of desired perennial grasses, thus allowing weeds a competitive edge over winter annuals.

5) Thatch buildup or shading--such conditions can contribute to stand thinning, thus allowing encroachment of weedy plants.

6) Mowing--height, timing, and type of mowing can weaken stand persistence and increase susceptibility to weed encroachment.

7) Soil- and root-infesting insects--white grubs, the young immature larvae of the brown May (and June) beetles, and nematodes, for example, often infest grass sod, feeding on roots. Heavy infestations can severely weaken stands of desirable vegetation.

Channel Vegetal Composition and Control Management Practices

Where existing plant species composition is not desirable, efforts should be made to introduce more desirable species. Depending on management objectives, interseeding, fertilization, herbicides, hand grubbing, mowing, and/or haying can be used independently or in combination to change vegetal composition (Herbel 1983).

Interseeding

The introduction of new species into existing stands of vegetation requires that (1) the introduced species is highly competitive, (2) the area to be interseeded is cleared of existing plant residue either by burning or by mechanical or chemical removal, (3) contact and preemergence herbicides (Martin et al. 1982; McMurphy 1969; Robinson and Greene 1976; Samson and Moser 1982) are used to surpress existing competition and prevent a weed infestation, and (4) proper planting rates and dates of planting are used.

Because of channel erosion potential, interseeding should be done with minimal disturbance of the soil. The success of interseeding depends on the kind of treatments done before or during planting to remove competition from existing vegetation.

Fertilization

Channel vegetal composition may be changed simply by timed and controlled application of fertilizers: lime, nitrogen alone, or a combination of nitrogen (N) plus potassium (K), phosphorus (P), or lime. Soil tests determine the amount of nutrients applied to a particular site through fertilization. Over most of the West, soil K and calcium (Ca) levels are usually adequate for good grass growth. Much of the Midwest, Northeast, Southeast, and the Northern Pacific Coast, however, generally require both lime and K in addition to N and P.

Soil fertility requirements, especially for P, K, and Ca, should be met before establishing the grass lining for a channel. The more mobile N can be added as needed in spring, fall, or split spring/fall applications. The best time to apply fertilizer is determined by the kind of grass, the amount and distribution of rainfall, and the kind of fertilizer being applied. Nitrogen fertilizer, when other essential nutrients are adequate, is the most important grass maintenance practice. Single spring and split spring/fall applications of N are beneficial on a number of warm-season, as well as cool-season, grasses. Although summer applications of N may be beneficial on certain warm-season grasses, for example, bermudagrass, they may be damaging to cool-season grasses. Cool-season grasses are usually fertilized in the fall and again in early spring for maximum growth. Excessive once yearly N-application rates should not be used for grass-lined channels. Rates between 30 and 60 lb of N per acre applied in early spring and again in the fall should maintain most warm- and cool-season grasses in excellent condition. Fertilization can be a long-time cure, a preventive measure, and/or a temporary solution.

Selective Herbicides

The success in controlling undesirable plants with herbicides depends on the correct identification of the target plant(s) and the use of the right herbicide applied at the right time. It is unlawful for any person to use any registered pesticide in a manner inconsistent with its label. The USDA "Compilation of Registered Uses of Herbicides" (Carter 1980) lists a number of selective herbicides for use on roadsides, highway rights-of-way, drainage ditches, pasture, rangeland, and turf (lawns). Some herbicides are approved in certain States for preemergence use in the establishment of certain grasses. A selective sampling of the extensive literature (Kay 1971; Martin et al. 1982; McMurphy 1969; Moomaw and Martin 1978; Robinson and Greene 1976; Samson and Moser 1982; Smith 1983) on the use of selective herbicides in the establishment of grasses is sufficient to show that considerable attention is being given the subject. Grass seedlings are, however, rate sensitive, and labeled application rates of approved use chemicals should not be exceeded.

The use of selective herbicides and fertilizers to shift vegetal composition, for example, removing undesirable grass competition, is a well-established science. Herbicide applications in grass-lined water channels may be questioned, however, for fear of stream and reservoir pollution.

Mowing

Mowing properly timed may aid in the control (especially during establishment) of certain weedy annual grasses and broadleaf weeds while preventing seed formation of undesirable species. Occasionally grass-lined channels may need to be mowed to maintain flow capacity. The frequency of mowing depends on the reason for mowing--whether to cause vegetation changes in the channel, control weeds, improve cover uniformity, or increase channel capacity. Other hydrologic and hydraulic factors related to channel use may also need to be considered in determining the timing and frequency of mowing and other maintenance practices. Removing vegetative growth as hay at times helps prevent undesirable thatch accumulation.

Frequent mowing to eliminate invading taller growing species (forbs and grasses) leads to a stand cover of lower growing sod grasses, such as bermudagrass and buffalograss. Mowing to reduce undesirable plant competition is a means of maintaining a desired composition of channel grasses.

Burning

Burning can be an excellent management tool to remove thatch, but it is potentially dangerous not only to vegetation ground cover of the burned site but also to those doing the burning and the public unless prescribed procedures are followed (Wright and Bailey 1980). Burning must be supervised and should conform with the requirements of any local fire authority.

If burning is used, plan to burn at a proper time. Use moist mulch; wind should be sufficient (5 mi/hr, but less than 10 mi/hr) to carry the fire rapidly; and manpower and equipment should be available to control the fire. Weather conditions (45 to 60 percent relative humidity, wind less than 10 mi/hr, air temperature of 40 to 60°F) during burn are extremely important. Timed properly with soil moisture and moist mulch present, burning is not injurious to most warm-season grasses. Burning should be done in the early spring about the time regrowth begins. Mulch of old vegetation must be dry enough to burn, but moist enough to reduce plant crown injury. If channels are burned too early in the spring, considerable time may elapse before vegetative regrowth. Thus, with soil exposed, runoff following heavy early-spring rains may damage the channel. Grass-lined channels established to cool-season grasses can be severely damaged by spring burns. Burning of these grasses, if necessary, should be done only in late summer or early fall.

Burning aids in weed, insect, and disease control. Not only does it allow complete thatch removal, it increases the effectiveness of fertilizer and herbicide applications and results in more uniform spring (warm-season) and fall (cool-season) growth. In certain situations it is an efficient way to decrease undesirable vegetation and promote desirable species.

ADDITIONAL CONSIDERATIONS

The design engineer must consider design risks when relying on grass(es) as the stabilizing medium. The designer should--

1) Plan the channel to make maximum use of existing acceptable vegetation.

2) Use side slopes of 2:1 or flatter to enhance seeding and establishment of vegetation.

3) Require berms and spoil areas to be graded to minimize or eliminate flow of surface water over channel side slopes.

4) Plan inlet structures, riprapped curves, culvert outlet protection, and so on, to minimize disruption of flows and thus reduce attack on vegetated boundaries.

5) Include construction of 50-100 ft of lateral channels in the prime contract when laterals are scheduled for later construction, so that vegetation on the main channel is not disturbed at the later date.

6) Schedule construction of the channel to coincide with optimum seeding dates.

7) Include seeding specifications in the contract for early seeding and optimum moisture conditions in side slopes.

8) Consider use of diversions, temporary plugs with small culverts, or other means to limit velocity in the channel until a vegetative cover is established.

Conditions that may prevent the use of grass as an effective lining for channel stabilization are (unpublished, USDA ENG.-Committee 2-5 draft of Proposal No. 4 - Vegetation as a Channel Stabilizer, 1971):

1) The climate will not support a sufficient cover of herbaceous vegetation to provide year-round protection.

2) The soils in the channel side slope are highly erodible and not capable of supporting permanent vegetation.

3) Channel base flows prevent the use of grass vegetation as a stabilizer for the channel bed.

4) Channel designs are not sufficient to handle design flows, thus increasing the risk of scouring.

Table 2.1
Characteristics of selected grass species for use in channels and waterways

Grass species	Growth habit		Roots		Adaptation				Establishment				Height at maturity
					Site		Soil		Seed		Rhizome or stolons		
	Bunch	Sod	Fibrous	Rhizomes-stolons	Lowland	Upland	Sandy	Silt-clay	Fast	Slow	Fast	Slow	ft
Cool-Season Grasses													
Creeping foxtail <u>Alopecurus</u> <u>arundinaceus</u> Poir.		+		+	+			+		+			3-4
Crested wheatgrass <u>Agropyron</u> <u>desertorum</u> (Fisch. ex Link) Schult.	+		+			+		+		+			2-3
Green needlegrass <u>Stipa</u> <u>viridula</u> Trin.	+		+			+		+		+			3-4
Russian wildrye[1] <u>Psathyrostachys</u> <u>junceus</u> (Fisch.) Nevski	+		+			+		+		+		+	3-4
Smooth bromegrass[2] <u>Bromus</u> <u>inermis</u> Leyss.		+		+		+		+	+				3-4
Tall fescue <u>Festuca</u> <u>arundinacea</u> Schreb.	+		+		+	+		+	+				3-4
Tall wheatgrass[1] <u>Elytriga</u> <u>pontica</u> (Podp.) Holub	+		+			+		+		+			4-5
Western wheatgrass[1] <u>Agropyron</u> <u>smithii</u> Rydb.		+		+	+	+		+		+	+		2-3
Warm-Season Grasses													
Bermudagrass <u>Cynodon</u> <u>dactylon</u> (L.) Pers.		+		+	+	+	+	+	+		+		3/4-2
Big bluestem <u>Andropogon</u> <u>gerardii</u> Vitm.		+		+	+	+		+		+		+	4-6
Blue grama <u>Bouteloua</u> <u>gracilis</u> (H.B.K.) Lag. ex Steud.		+	+			+		+		+			1-2
Buffalograss <u>Buchloe</u> <u>dactyloides</u> (Nutt.) Engelm.		+		+		+		+	+		+		1/3-1

Green sprangletop Leptochloa dubia (H.B.K.) Nees	+		+			+	+	+	+			3-4
Indiangrass Sorghastrum nutans (L.) Nash		+		+	+	+	+	+	+		+	5-6
Kleingrass Panicum coloratum L.	+		+			+		+		+		3-4
Little bluestem Schizachyrium scoparium (Michx.) Nash		+				+	+	+	+		+	3-4
Plains bristlegrass Setaria macrostachya H.B.K.	+		+			+	+	+		+		1-2
Sand bluestem Andropogon hallii Hack.		+		+	+	+	+			+	+	5-6
Sideoats grama Bouteloua curtipendula (Michx.) Torr.	+			+		+	+	+	+		+	2-3
Switchgrass[3] Panicum virgatum L.		+		+	+	+	+	+	+		+	4-5
Vine mesquitegrass Panicum obtusum H.B.K.		+		+		+		+		+	+	1-2
Weeping lovegrass Eragrostis curvula (Schad.) Nees	+		+			+	+		+			3-4
Old World Bluestems[4]												
Caucasian bluestem Bothriochloa caucasica (Trin.) C.E. Hubb.	+		+		+	+		+	+			4-5
'Ganada' yellow bluestem Bothriochloa ischaemun var. ischaemun	+		+		+	+		+	+			3-4

Table 2.1--Continued
Characteristics of selected grass species for use in channels and waterways

Grass species	Growth habit		Roots		Adaptation: Site		Adaptation: Soil		Establishment: Seed		Establishment: Rhizome or stolons		Height at maturity ft
	Bunch	Sod	Fibrous	Rhizomes-stolons	Lowland	Upland	Sandy	Silt-clay	Fast	Slow	Fast	Slow	
Old World Bluestems--Con.													
'King Ranch' yellow bluestem *Bothriochloa ischaemun* var. *songarica* (Rupr. ex Fisch. + May.) Celar. + Harlan	+		+			+		+	+				3-4
'Plains' yellow bluestem *Bothriochloa ischaemun* var. *ischaemun*	+		+		+	+		+	+				3-4
'WW-Sparr' yellow bluestem *Bothriochloa ischaemun* var. *ischaemun*	+		+		+	+	+	+	+				3-4

[1] Alkali tolerance good.
[2] Two types: Northern and Southern.
[3] Two types: upland, for example, 'Blackwell', and lowland, 'Kanlow'.
[4] Wide differences within species; select strains that are adapted and meet planting objectives.

3. DETERMINATION OF CHANNEL DESIGN PARAMETERS

By D.M. Temple

The conditions governing the stability of a grass-lined open channel are the channel geometry and slope, the erodibility of the soil boundary, and the properties of the grass lining that relate to flow retardance potential and boundary protection. Design relations based on consideration of these conditions are presented in chapter 1, along with discussions of the theory and logic required for their development. Discussions in this chapter will focus on using information normally available during the design stage of a project to estimate the vegetal and soil parameters required for application of these relations.

VEGETAL PARAMETERS

Stability design of a grass-lined open channel by effective stress requires the determination of two vegetal parameters. The first is the retardance curve index which describes the potential of the vegetal cover to develop flow resistance. The second is the vegetal cover factor which describes the degree to which the vegetal cover prevents high velocities and stresses at the soil-water interface. Although some of the same considerations, such as vegetal density, will influence both parameters, the actions and the parameters may be considered as essentially independent.

Retardance Potential

The parameter describing the retardance potential of a vegetal cover is the retardance curve index C_I. This parameter enters the flow resistance computations through equation 1.2 and determines the limiting vegetal stress through equation 1.17. Its relation to the measurable physical properties of the vegetal cover is given by equation 1.3 as:

$$C_I = 2.5 \ (h\sqrt{M})^{1/3} \qquad (1.3)$$

in which h is the representative stem length and M is the stem density in stems per unit area. When consistent units are used, the relation is dimensionless.

The stem length will usually need to be estimated directly from knowledge of the vegetal conditions at the time of anticipated maximum flow. The information in table 2.1 may be used as a guide for the grass species most commonly encountered. When two or more grasses with widely differing growth characteristics are involved, the representative stem length is determined as the root mean square of the individual stem lengths.

When equation 1.3 is used to estimate the retardance potential, an estimate of the stem density is required. The reference stem densities contained in table 3.1 may be used as a guide in estimating this parameter when more direct information is unavailable. The values of reference stem density contained in this table were obtained from a review of the available qualitative descriptions and stem counts reported by researchers studying channel resistance and stability. A more detailed discussion of the development of this table is given by Temple (1982).

For brushy and/or branching types of vegetation such as alfalfa, the definition of a "stem as seen by the flow" becomes more difficult. Although equation 1.3 may still be used for these covers as suggested in the footnotes to table 3.1, the experienced designer may find use of the traditional SCS retardance classes preferable (SCS 1954). Table 3.2 is provided to allow experience to be applied in this fashion.

Since cover conditions will vary from year to year and season to season, establishing an upper and a lower bound for the curve index is often more realistic than selecting a single value. When this approach is taken, the lower bound should be used in stability computations and the upper bound should be used in determining channel capacity. Such an approach will normally result in satisfactory operation for lining conditions between the specified bounds. Whatever the approach used to obtain the flow retardance potential of the lining, the value(s) selected should represent an average for the channel reach in question since it will be used to infer an average energy loss per unit of boundary area for any given flow.

Vegetal Cover Factor

The vegetal cover factor C_F is used to describe the degree to which the vegetal cover prevents high velocities and stresses at the soil-water interface. It enters the channel stability computations through equation 1.13. Because the protective action described by this parameter is associated with the prevention of local erosion damage which may lead to channel unraveling, the cover factor should represent the weakest area in a reach rather than an average for the cover.

Observation of flow behavior and available data indicate that the cover factor is dominated by the density and uniformity of density in the immediate vicinity of the soil boundary. Its sensitivity to cover uniformity has thus far thwarted attempts to develop expressions relating its value to realistically measurable properties of the vegetal cover. For relatively dense and uniform covers, uniformity of density is primarily dependent on the growth characteristics of the cover, which are in turn related to grass type. This relationship is exploited in the development of table 3.1. A tabular function such as that presented in table 3.1 obviously cannot account for such considerations as maintenance practices or uniformity of soil fertility or moisture. Therefore, appropriate engineering judgment should be used in its application.

SOIL PARAMETERS

Two soil parameters are required for application of effective stress concepts to the stability design of lined or unlined channels having an erodible soil boundary: Soil grain roughness and allowable effective stress. When the effective stress approach is used, the soil parameters are the same for both lined and unlined channels satisfying the sediment transport restrictions outlined in chapter 1. Therefore, an engineer experienced with local conditions may wish to use alternative sources of information for estimating these parameters. The relations presented here are taken from the SCS (1977) channel stability criteria in the fashion described in chapter 1. The desired parameters, soil grain roughness and allowable stress, are determined from more basic soil parameters. Ideally, the basic parameters are determined from tests on representative samples. When such test data are not available, however, more general soils classification information such as the SOILS-5 data available through the Soil Conservation Service may be useful.

For effective stress design, soil grain roughness is defined as that roughness associated with particles or aggregates of a size that may be independently moved by the flow at incipient channel failure. Although this parameter is expressed in terms of a flow resistance coefficient (n_s), its primary importance in design of vegetated channels is its influence on effective stress as expressed by equation 1.13. Its contribution to the total flow resistance of a grass-lined channel is usually negligibly small (see discussion of eq. 1.4).

The allowable stress is key to the effective stress design procedure. It is defined as that erosionally effective stress above which an unacceptable amount of particle or aggregate detachment would occur. The use of an erosionally effective stress implies that considerations of particle pressure drag and time-space variations in actual tractive force are directly or indirectly included. It is, therefore, not a stress in the strictest sense, but this fact does not detract from its utility as a design tool.

Noncohesive Soil

For purposes of determining the soil grain roughness and allowable stress, noncohesive soil is divided into fine- or coarse-grained soil according to the diameter for which 75 percent of the material is finer (d_{75}). Ideally, the point of division for hydraulic purposes would define the point at which particle submergence in the viscous boundary layer causes pressure drag to become negligible. Strict identification of this point is impractical for channel design applications, however. For practical application in computing soil grain roughness and allowable effective stress, noncohesive soils are defined as fine- or coarse-grained according to whether d_{75} is less than or greater than 0.05 in. For fine-grained soils, the soil grain roughness and allowable effective stress are constant, while for a coarse-grained soil, these parameters are a function of particle size. The required parameters are given in graphical form in figures 3.1 and 3.2 and in equational form in table 3.3.

Cohesive Soil

All cohesive soil is treated as fine-grained soil having a constant soil grain roughness. The allowable effective stresses presented here are taken directly from SCS (1977) permissible velocity design criteria under the assumptions discussed in chapter 1. The soil properties required to determine the allowable effective stress are the soil's classification in the unified soil classification system, its plasticity index (I_w), and its void ratio (e). The information required to estimate allowable effective stress from these properties is given in graphical form in figures 3.3 and 3.4 and in equational form in table 3.3. Application requires that a basic allowable effective stress (τ_{ab}) be determined from the soil classification and plasticity index. This basic value is then corrected for void ratio according to the relation:

$$\tau_a = \tau_{ab} C_e^2 \qquad (3.1)$$

where C_e is the void ratio correction factor determined from figure 3.4 or the appropriate relation from table 3.3.

Table 3.1
Properties of grass channel linings; values apply to good uniform stands of each cover[1]

Cover factor C_F	Covers tested	Reference stem density ($stem/ft^2$)
0.90	bermudagrass	500
	centipedegrass	500
.87	buffalograss	400
	kentucky bluegrass	350
	blue grama	350
.75	grass mixture	200
.5	weeping lovegrass	350
	yellow bluestem	250
.5	alfalfa[2]	500
	lespedeza sericea[2]	300
.5	common lespedeza	150
	sudangrass	50

[1]Multiply the stem densities given by 1/3, 2/3, 1, 4/3, and 5/3, for poor, fair, good, very good, and excellent covers, respectively. The equivalent adjustment to C_F remains a matter of engineering judgment until more data are obtained or a more analytic model is developed. A reasonable, but arbitrary, approach is to reduce the cover factor by 20 percent for fair stands and 50 percent for poor stands. C_F values for untested covers may be estimated by recognizing that the cover factor is dominated by density and uniformity of cover near the soil surface. Thus, the sod-forming grasses near the top of the table exhibit higher C_F values than the bunch grasses and annuals near the bottom.

[2]For the legumes tested, the effective stem count for resistance (given) is approximately five times the actual stem count very close to the bed. Similar adjustment may be needed for other unusually large-stemmed, branching, and/or woody vegetation.

Table 3.2
Retardance curve index by SCS (1954) retardance class

SCS retardance class	Retardance curve index C_I
A	10.0
B	7.64
C	5.60
D	4.44
E	2.88

Table 3.3
Equations for determining allowable effective stress[1]

Soil classification	Applicable range	Equation
Noncohesive soils GW,GP,SW,SP	$I_w < 10$	
	$d_{75} < 0.05$	$n_s = 0.0156$ $\tau_a = 0.02$
	$0.05 \leq d_{75}$	$n_s = 0.0256\ d_{75}^{1/6}$ $\tau_a = 0.4\ d_{75}$
Cohesive soils	$10 < I_w$	$n_s = 0.0156$ $\tau_a = \tau_{ab}\ C_e^2$
GM,SC		$C_e = 1.42 - 0.61\ e$
	$10 \leq I_w \leq 20$	$\tau_{ab} = (1.07\ I_w^2 + 14.3\ I_w + 47.7) x 10^{-4}$
	$20 < I_w$	$\tau_{ab} = 0.076$
GC		$C_e = 1.42 - 0.61\ e$
	$10 \leq I_w \leq 20$	$\tau_{ab} = (0.0477\ I_w^2 + 2.86\ I_w + 42.9) x 10^{-3}$
	$20 < I_w$	$\tau_{ab} = 0.119$
SM		$C_e = 1.42 - 0.61\ e$
	$10 \leq I_w \leq 20$	$\tau_{ab} = (1.07\ I_w^2 + 7.15\ I_w + 11.9) x 10^{-4}$
	$20 < I_w$	$\tau_{ab} = 0.058$

Table 3.3--Continued
Equations for determining allowable effective stress[1]

Soil classification	Applicable range	Equation
CH		$C_e = 1.38 - 0.373\ e$
		$\tau_{ab} = 0.0966$
CL		$C_e = 1.48 - 0.57\ e$
	$10 \leq I_w \leq 20$	$\tau_{ab} = (1.07\ I_w^2 + 14.3\ I_w + 47.7) \times 10^{-4}$
	$20 < I_w$	$\tau_{ab} = 0.076$
MH		$C_e = 1.38 - 0.373\ e$
	$10 \leq I_w \leq 20$	$\tau_{ab} = (0.0477\ I_w^2 + 1.43\ I_w + 10.7) \times 10^{-3}$
	$20 < I_w$	$\tau_{ab} = 0.058$
ML		$C_e = 1.48 - 0.57\ e$
	$10 \leq I_w \leq 20$	$\tau_{ab} = (1.07\ I_w^2 + 7.15\ I_w + 11.9) \times 10^{-4}$
	$20 < I_w$	$\tau_{ab} = 0.058$

Table 3.3--Continued
Equations for determining allowable effective stress[1]

Soil classification	Applicable range	Equation
OH		$C_e = 1.0$
	$10 \leq I_w \leq 20$	$\tau_{ab} = (0.0477\ I_w^2 + 1.43\ I_w + 10.7) \times 10^{-3}$
	$20 < I_w$	$\tau_{ab} = 0.058$
OL		$C_e = 1.0$
	$10 \leq I_w \leq 20$	$\tau_{ab} = (1.07\ I_w^2 + 7.15\ I_w + 11.9) \times 10^{-4}$
	$20 < I_w$	$\tau_{ab} = 0.058$

[1]English units = d_{75} in inches; τ_a and τ_{ab} in lb/ft^2

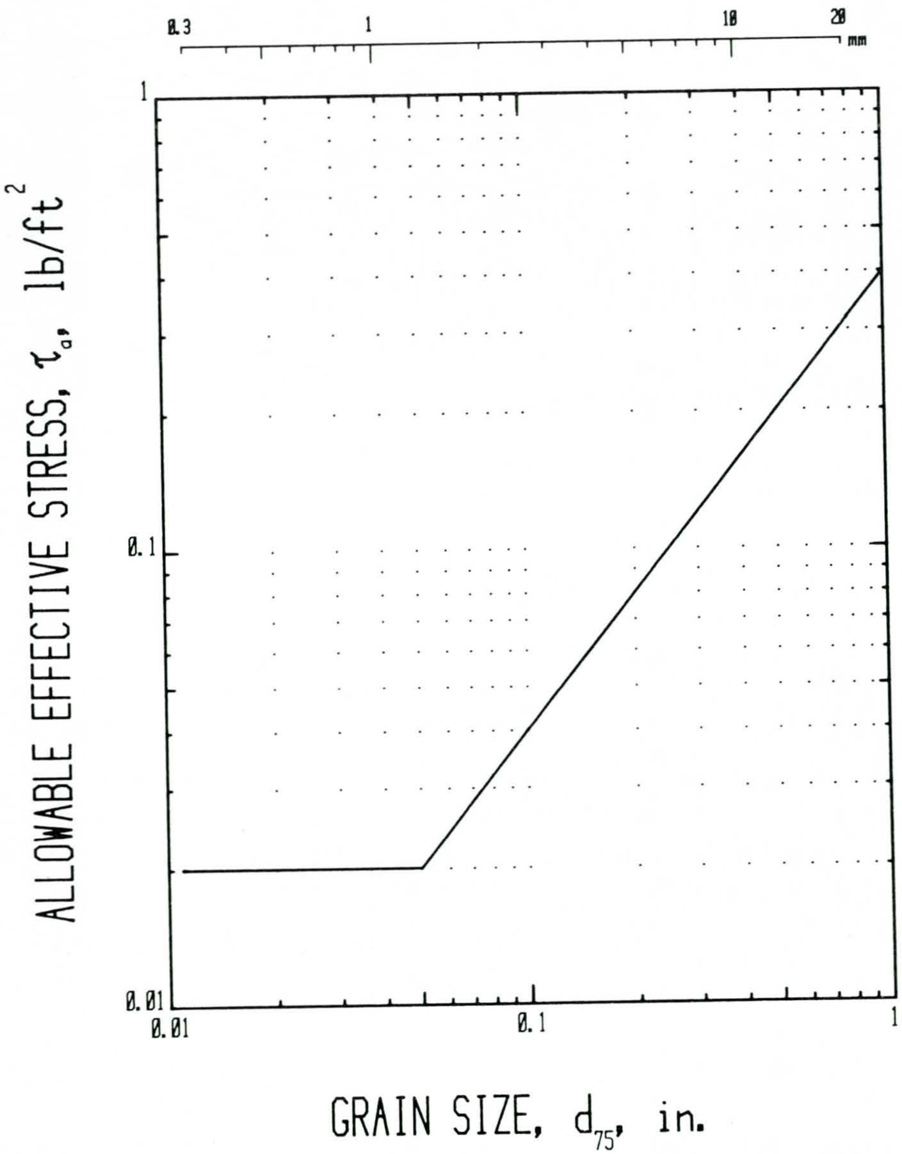


Figure 3.1
Allowable effective stress for
noncohesive soils.

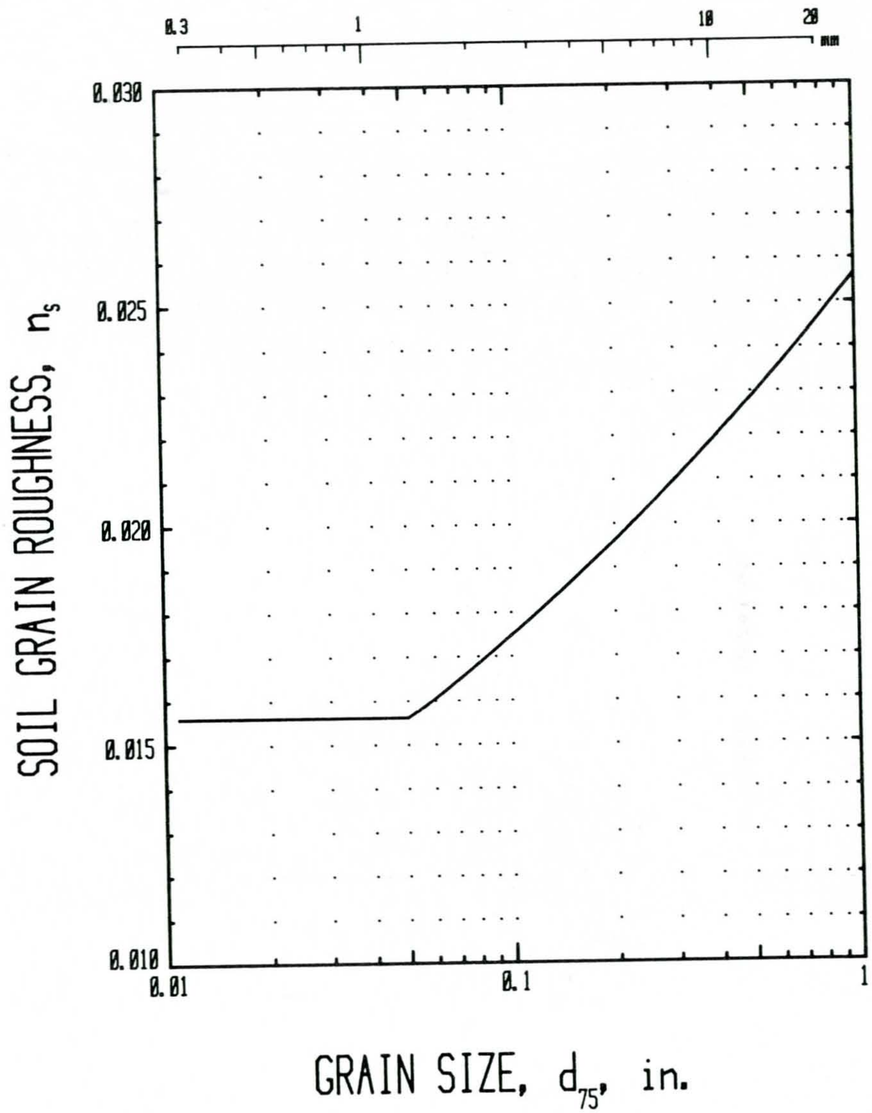


Figure 3.2
Soil grain roughness for
noncohesive soils.

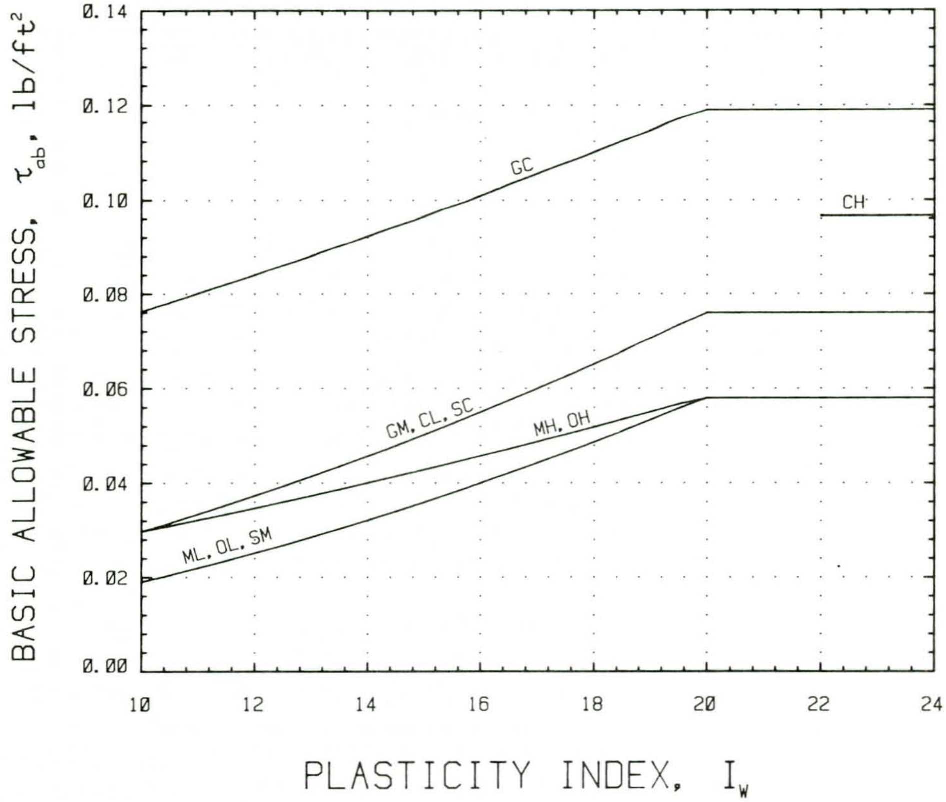


Figure 3.3
Basic allowable effective stress for cohesive soils (compiled from SCS (1977) Permissible Velocities).

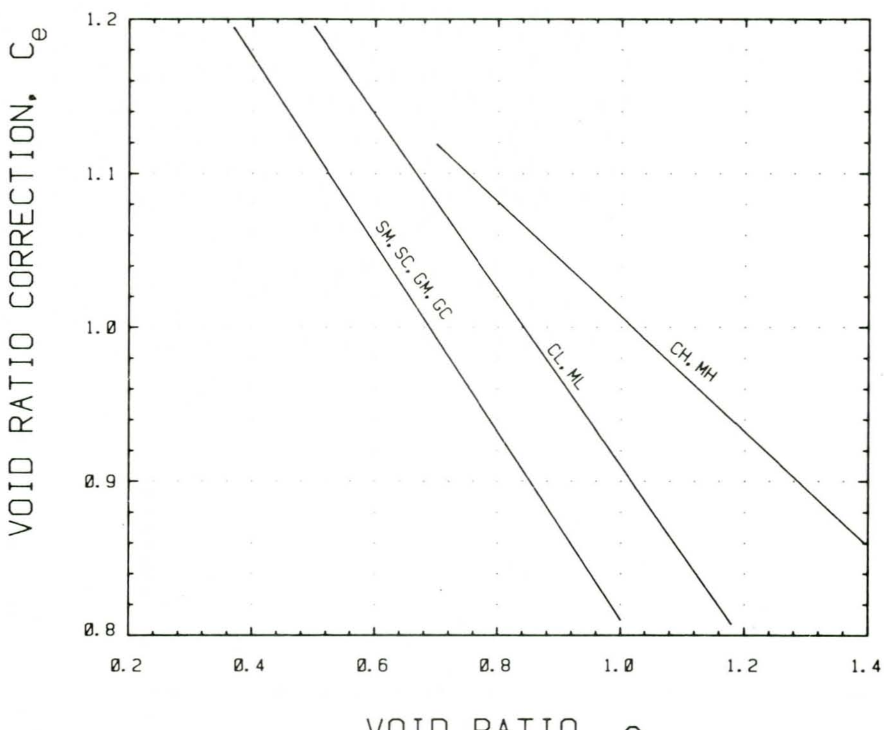


Figure 3.4
Void ratio correction factor for cohesive soils (after SCS (1977)).

4. GRASS-LINED CHANNEL DESIGN

By D.M. Temple

The design of a grass-lined open channel differs from the design of an unlined or structurally lined channel in that (1) the flow resistance is dependent on channel geometry and discharge, (2) a portion of the boundary stress is associated with drag on individual vegetal elements and is transmitted to the erodible boundary through the plant root system, and (3) the properties of the lining vary both randomly and periodically with time. Each of these differences requires special consideration in the design process. The procedures and examples presented in this chapter illustrate the way in which these special considerations may be integrated into the design process.

The generalized step-by-step computational procedure outlined in this chapter (pp. 55 and 62) forms the basis for the computational routines discussed in chapter 5.

Numerically, stability dependent channel design may be viewed as the solution of a set of simultaneous equations relating channel geometry and flow conditions to boundary stress. In this context, the dependence of flow resistance on channel geometry and discharge is accounted for through the introduction of one additional equation (eq. 1.2) and one additional variable (C_I).

The transmission of stress to the boundary via the plant root system is accounted for through a modification of the effective stress relation (eq. 1.13) and an additional limit check for identification of conditions where stress on the lining rather than stress on the erodible boundary limits stability (eqs. 1.17 and 1.18). The time variability of vegetal cover conditions is accounted for in the computational procedure through the use of different cover conditions to determine the required channel width and depth. Minimum estimated cover (minimum C_I and C_F) is assumed to determine channel width as a shape-dependent function of depth (stability). Maximum estimated cover conditions are used to compute the required depth (capacity).

Using the effective stress approach, the problem of designing a channel for stability is one of obtaining the solution to a set of nonlinear simultaneous equations that may be expressed functionally as:

$$n = n(V,R,C_I) \tag{4.1}$$

$$V = V(R,n,S) \tag{4.2}$$

$$\tau_e = \tau_e(D,S,C_F,n_s,n) \tag{4.3}$$

$$Q = Q(V,D,T) \tag{4.4}$$

$$R = R(D,T) \tag{4.5}$$

Since this set of relations consists of 5 independent relations in 11 variables, 6 of the variables must be specified. Normally, the specified variables are the channel energy slope (S), the design discharge (Q), the grass conditions as described by the retardance curve index (C_I) and the vegetal cover factor (C_F), and the soil conditions as described by the allowable stress ($\tau_e = \tau_a$ for stability limited design) and the soil grain roughness (n_s). The variables to be solved for are then the flow resistance (n), the mean flow velocity (V), the flow depth (D), the hydraulic radius (R), and the channel width (T) at a distance D above the bed. Other groupings of the dependent and independent variables are, of course, possible with the same set of relations.

Two-Dimensional Flow

The equations representing the shape-dependent relations 4.4 and 4.5 are reduced to their simplest form under the limiting condition of two-dimensional flow.[4] This condition will be used, therefore, to illustrate the considerations required for correct application of the design relations. For two-dimensional flow, the system of simultaneous equations may be written as:

---

[4]Two-dimensional flow considerations are approximated in reality in a very wide flat-bottomed channel. This condition, therefore, is often referred to as the wide-channel condition.

$$n = \exp\{C_I(0.0133\ [\ln(VR)]^2 - 0.0954\ \ln(VR) + 0.297) - 4.16\} \qquad (4.1a)$$

$$V = \frac{1.49}{n} R^{2/3} S^{1/2} \qquad (4.2a)$$

$$\tau_a = \gamma DS(1-C_F)(n_s/n)^2 \qquad (4.3a)$$

$$Q = V\ D\ T \qquad (4.4a)$$

$$R = D \qquad (4.5a)$$

within the limits discussed in chapter 1. Assuming the set of dependent and independent variables described above and applying appropriate algebraic manipulation, this system may be solved for a maximum stable unit discharge or minimum stable width given by the relations:

$$q = \exp\left\{\frac{-b-\sqrt{b^2-4ac}}{2a}\right\} \qquad (4.6a)$$

in which:

$$a = 0.0133\ C_I$$

$$b = -(0.0954\ C_I + 0.429)$$

$$c = 0.297\ C_I - 0.5\ln(S) + 0.714\ \ln\left\{\frac{\tau_a}{(1-C_F)n_s^2}\right\} - 6.94$$

and

$$T = Q/q \qquad (4.7a)$$

Other unknown variables (V,D,n) may be easily obtained from minor variation of members of the original equation set once the unit discharge (q=VD) has been determined.

The applicability of equation 4.6a is limited to the range of conditions for which equations 4.1a through 4.5a are valid. These limits are discussed in chapter 1 and may be written as:

$$0.0025\ C_I^{2.5} \leq q \leq 36 \qquad (4.8a)$$

and

$$\gamma DS \leq \tau_{va}+\tau_e \tag{4.9a}$$

where τ_{va} is a known function of vegetal conditions (eq. 1.17).

Equation 4.8a is a limitation on the applicability of equation 4.1a. Therefore, in the rare event that these conditions are violated, equation 4.1a must be replaced in the system. When this happens, it is normally assumed that Manning's n is constant and equal to its value at the nearest boundary (that is, n is computed from equation 4.1a with VR equal to 0.0025 $C_I^{2.5}$ if $q < 0.0025\ C_I^{2.5}$ and with VR equal to 36 if $q > 36$). Under this assumption, n may be treated as a known quantity and the remaining relations solved to yield:

$$q = \frac{0.0015\ \tau_a^{5/3}\ n^{7/3}}{(1-C_F)^{5/3}\ n_s^{10/3}\ S^{7/6}} \tag{4.6b}$$

Failure to satisfy relation 4.9a indicates that channel failure will begin as a result of stress on the grass lining itself rather than as a result of stress on the soil boundary. Equation 4.3a of the system, therefore, must be replaced since it is no longer a governing relation. For the usual condition where $\tau_{va} >> \tau_a$, the vegetal stress relation may be written as:

$$\tau_v = \tau_{va} \cong \tau = \gamma DS \tag{4.3c}$$

resulting in the modified form given by:

$$q = \exp \frac{-b+\sqrt{b^2-4ac}}{2a} \tag{4.6c}$$

where:

$$a = 0.0133\ C_I$$

$$b = 1-0.0954\ C_I$$

$$c = 0.297\ C_I-1.67\ell n(\tau_{va})+1.17\ell n(S)+2.33$$

The final case that must be considered is when neither relation 4.8a nor 4.9a is satisfied. For this condition, the system degenerates to the form of the allowable total stress problem applicable to very coarse noncohesive material, and the allowable unit discharge is given by:

$$q = \left\{ \frac{0.0015 \; \tau_{va}^{5/3}}{n \; S^{7/6}} \right\} \qquad (4.6d)$$

Computational Procedure

Although equations corresponding to functional relations 4.4 and 4.5 may be written for the typical channel shapes used in design, the approach of directly solving the resulting simultaneous equations is not found to be the most efficient for general application. The reason for this is the complexity of the resulting set of nonlinear equations and the number of cases that would need to be considered. Practical considerations related to construction, maintenance, bank slope stability, and so on, will normally introduce at least one additional limiting relation, thereby doubling the number of cases requiring consideration for complete solution of the mathematical problem. Therefore, an iterative solution scheme that allows correct equation selection at each step has been developed and follows in outline form.

The equations required to apply the iterative procedure for the design of triangular, trapezoidal, or parabolic channels are incorporated into the outline for convenient application. See appendix A for the definition of variables introduced as a result of the inclusion of the shape-dependent equations and limits.

I. Stability Design Parameter Determination

A. Determine design discharge (Q)

B. Determine required channel slope (S)

C. Specify channel shape

1. Trapezoidal with bank slope and minimum width (B_{min}) specified
2. Triangular with maximum bank slope (Z_{min}) specified
3. Parabolic with maximum bank slope (Z_{min}) specified (Z_{min} specified at water surface for parabolic channels)

D. Determine soil parameters for design
(equations for determining soil parameters are given in table 3.3, p. 46)

1. Allowable stress (τ_a)
   a. Noncohesive soil
      Figure 3.1, p. 49
   b. Cohesive soil
      Figures 3.3, p. 50, and 3.4, p. 50, with
      $\tau_a = \tau_{ab} C_e^2$
2. Soil grain roughness (n_s)
   a. Noncohesive soil
      Figure 3.2, p. 49
   b. Cohesive soil
      $n_s = 0.0156$

E. Determine vegetal cover parameters

1. Retardance curve index (C_I)
   $C_I = 2.5(h\sqrt{M})^{1/3}$ with table 3.1, p. 44, or table 3.2, p. 45
2. Vegetal cover factor (C_F)
   table 3.1, p. 44
3. Allowable vegetal stress (τ_{va})
   $\tau_{va} = 0.75\ C_I$

II. First Iteration Estimates of Channel Geometry and Mean Velocity

(Estimates based on judgment or experience may be used in lieu of the suggested relations)

A. Solve the two-dimensional flow relations
   1. Unit discharge and flow resistance
      a. Stability controlled by allowable soil stress

$$q > 36 \begin{cases} n = \exp(0.126\ C_I - 4.16) \\ q = \dfrac{0.0015\ \tau_a\ n^{7/3}}{(1-C_F)^{5/3}\ n_s^{10/3}\ S^{7/3}} \end{cases}$$

$$0.0025\ C_I^{2.5} \le q \le 36 \begin{cases} q = \exp\left\{\dfrac{-b-\sqrt{b^2-4ac}}{2a}\right\} \\ a = 0.0133\ C_I \\ b = -(0.0954\ C_I + 0.429) \\ c = 0.297 C_I - 0.5\ \ell n(S) \\ \qquad +0.714 \ell n \left\{\dfrac{\tau_a}{(1-C_F) n_s^2}\right\} - 6.94 \\ n = \exp\{C_I(0.0133[\ell n(q)]^2 - 0.0954 \ell n\ (q) \\ \qquad +0.297)\ -4.16\} \end{cases}$$

$$q < 0.0025\ C_I^{2.5} \begin{cases} n = \exp\{C_I(0.0133[\ell n(0.0025\ C_I^{2.5})]^2 \\ \qquad -0.0954\ \ell n(0.0025\ C_I^{2.5}) + 0.297) - 4.16\} \\ q = \dfrac{0.0015\ \tau_a^{5/3}\ n^{7/3}}{(1-C_F)^{5/3}\ n_s^{10/3}\ S^{7/3}} \end{cases}$$

b. Stability controlled by allowable vegetal stress

$$q > 36 \begin{cases} n = \exp(0.126\ C_I - 4.16) \\ q = \dfrac{0.0015\ \tau_{va}^{5/3}}{n\ S^{7/6}} \end{cases}$$

$$0.0025\ C_I^{2.5} \le q \le 36 \begin{cases} q = \exp \dfrac{-b+\sqrt{b^2-4ac}}{2a} \\ \quad a = 0.0133\ C_I \\ \quad b = 1-0.0954\ C_I \\ \quad c = 0.297\ C_I + 1.17\ \ell n(S) - 1.67 \\ \qquad \ell n(\tau_{va}) + 2.33 \\ n = \exp\{C_I[0.0133[\ell n(q)]^2 - 0.0954 \\ \quad \ell n(q) + 0.297]\ -4.16\} \end{cases}$$

2. Width and depth with applicable q from step 1-a or 1-b

$$W = Q/q$$

$$D = \left\{ \frac{q\ n}{1.49\ S^{1/2}} \right\}^{0.6}$$

B. Estimate geometric control parameter
(W is the width at D/2)

1. Trapezoidal channel
(bed width, B, selected as control parameter)
$B = W - Z\ D$
2. Triangular channel
(bank side slope, Z, selected as control parameter)
$Z = W/D$
3. Parabolic channel
(coefficient a_p of $D = a_p(T/2)^2$ selected as control parameter)

$$a_p = \frac{2D}{W^2}$$

C. Check estimate of control parameter against specified limits

1. Trapezoidal channel

$$B \geq B_{min}$$

2. Triangular channel

$$Z \geq Z_{min}$$

3. Parabolic channel

$$a_p \leq \frac{1}{\sqrt{2}\, W\, Z_{min}}$$

D. Estimate mean velocity

$$V = q/D$$

III. Iterative Solution

A. Compute flow cross-sectional area

$$A = Q/V$$

B. Compute flow depth

1. Trapezoidal channel

$$D = \left\{ \frac{-B+\sqrt{B^2+4AZ}}{2Z} \right\}$$

2. Triangular channel

$$D = \sqrt{A/Z}$$

3. Parabolic channel

$$D = (0.75\, A\sqrt{a_p})^{2/3}$$

C. Compute hydraulic radius

1. Trapezoidal channel

$$R = \left\{ \frac{A}{B+2\, D\sqrt{Z^2+1}} \right\}$$

2. Triangular channel

$$R = \left\{ \frac{A}{2\, D\sqrt{Z^2+1}} \right\}$$

3. Parabolic channel

$$R = \left\{ \frac{A}{\sqrt{4D^2 + D/a_p} + \frac{1}{2a_p} \ell n(\sqrt{4a_pD} + \sqrt{4a_pD + 1})} \right\}$$

D. Compute Manning's n

$$n = \exp\{C_I(0.0133\ [\ell n(q_R)]^2 - 0.0954\ \ell n(q_R) + 0.297) - 4.16\}$$

where: $q_R = 36$ when $VR > 36$

$q_R = VR$ when $0.0025\ C_I^{2.5} \leq VR \leq 36$

$q_R = 0.0025\ C_I^{2.5}$ when $VR < 0.0025\ C_I^{2.5}$

E. Compute velocity by Manning's equation

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

F. Check velocity convergence
(compare V with V_m)

1. If velocity convergence is unacceptable, adjust velocity estimate and return to step III-A

$$V_{new} = V_{old} + 0.67(V_m - V_{old})$$

2. If $V \cong V_m$, then flow conditions are established for this channel

G. Compute boundary stresses
1. Effective soil stress

$$\tau_e = \gamma DS(1-C_F)(n_s/n)^2$$

2. Vegetal stress

$$\tau_v = \gamma DS - \tau_e$$

H. Check channel stability
1. If computed stresses are unacceptable, adjust the geometric control parameter and return to step III-A
2. If computed stresses are acceptable, the stability portion of the design is completed.

If design conditions are such that the cover condition used for stability design may also be considered to dictate capacity, the geometric design of the channel for uniform flow conditions is completed by adding an appropriate freeboard to the computed flow depth. If, however, a range of cover conditions is anticipated (the usual case), the important parameter established by the above procedure is the geometric control parameter of step III-H-1. The design flow depth must then be determined using the maximum anticipated value of the retardance curve index C_I.

The purpose of the capacity design computations is to establish the minimum flow depth or area required to attain the required discharge capacity under conditions of maximum anticipated flow resistance. The applicable set of simultaneous equations is the same as for stability design except that relation 4.3 is replaced by a shape-dependent function relating width to depth through the geometric control parameter established from stability considerations. The problems encountered in solution are also similar.

Two-Dimensional Flow

Because of the comparative simplicity of the relations involved, the case of two-dimensional flow again forms a logical starting point for the iterative computations. For this case, the geometric control parameter is channel width. This means that the unit discharge, q, computed by equation 4.7a is also a known constant. This fact allows equation 4.1a to be solved directly for flow resistance (by direct substitution, VR=VD=q). The flow depth, D, is then obtained by rewriting equation 4.2a in the form:

$$D = \left\{ \frac{q\ n}{1.49\ S^{1/2}} \right\}^{0.6} \qquad (4.10a)$$

Since n is solved for directly, the cases generated by limiting relation 4.8a may be accounted for directly in the computation of n. This degree of simplification is not achieved for the more complex channel shapes. Therefore, an iterative procedure is again utilized.

Computational Procedure

I. Capacity Design Parameter Determination

A. Use the discharge (Q), slope (S), and geometric control parameter determined by stability design
B. Determine applicable vegetal retardance curve index (C_I)

$C_I = 2.5\ (h\sqrt{M})^{1/3}$ with table 3.1, p. 44; or table 3.2, p. 45

II. First Iteration Estimate of Mean Velocity

(Estimates based on judgment or experience may be used in lieu of the suggested relations)

A. Solve the two-dimensional flow relations

1. Assume a unit discharge equal to the VR product obtained from stability computations

   $q = VR$

2. Compute Manning's n

$$n = \exp\{C_I(0.0133\ [\ell n(q_R)]^2 - 0.0954\ \ell n(q_R) + 0.297) - 4.16\}$$

where:

$q_R = 36$	when	$q > 36$
$q_R = q$	when	$0.0025\ C_I^{2.5} \leq q \leq 36$
$q_R = 0.0025\ C_I^{2.5}$	when	$q < 0.0025\ C_I^{2.5}$

3. Compute flow depth

$$D = \left\{\frac{q\ n}{1.49\ S^{1/2}}\right\}^{0.6}$$

B. Estimate mean velocity

   $V = q/D$

III. Iterative Solution

A. Compute flow cross-sectional area

   $A = Q/V$

B. Compute flow depth

1. Trapezoidal channel

$$D = \left\{\frac{-B+\sqrt{B^2+4AZ}}{2Z}\right\}$$

2. Triangular channel

$$D = \sqrt{A/Z}$$

3. Parabolic channel

$$D = (0.75\ A\sqrt{a_p})^{2/3}$$

C. Compute hydraulic radius

1. Trapezoidal channel

$$R = \left\{ \frac{A}{B+2\, D\sqrt{Z^2+1}} \right\}$$

2. Triangular channel

$$R = \left\{ \frac{A}{2\, D\sqrt{Z^2+1}} \right\}$$

3. Parabolic channel

$$R = \left\{ \frac{A}{\sqrt{4D^2 + D/a_p} + \frac{1}{2a_p}\, \ell n(\sqrt{4a_p D} + \sqrt{4a_p D + 1})} \right\}$$

D. Compute Manning's n

$$n = \exp\{C_I(0.0133\, [\ell n(q_R)]^2 - 0.0954\, \ell n(q_R) + 0.297) - 4.16\}$$

where: $q_R = 36$ when $VR > 36$

$q_R = VR$ when $0.0025\, C_I^{2.5} \leq VR \leq 36$

$q_R = 0.0025\, C_I^{2.5}$ when $VR < 0.0025\, C_I^{2.5}$

E. Compute velocity by Manning's equation

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

F. Check velocity convergence (compare V with V_m)

1. If velocity convergence is unacceptable, adjust velocity estimate and return to step III-A

$$V_{new} = V_{old} + 0.67(V_m - V_{old})$$

2. If $V \cong V_m$, then flow conditions are established for this channel

G. Add appropriate freeboard to the computed flow depth

H. Examine to assure that unnecessary problems will not be encountered in construction or maintenance

I. Analyze conditions at flow obstructions, constrictions, curves, and so on, using appropriate hydraulic procedures

EXAMPLE COMPUTATIONS

Although primary use of the outlined iterative procedure is through calculator or computer programs such as those described in chapter 5, convergence is usually quite rapid, making hand calculations possible without an unreasonable amount of repetition. For hand calculations, the use of the two-dimensional flow approximation for first estimates becomes increasingly important as shown by the following examples.

Example 1

Consider an emergency spillway channel for an on-farm reservoir with an outlet channel on a 2 percent slope. The channel is to be topsoiled with a CL soil having a plasticity index of 15, compacted to a void ratio of approximately 0.9. The spillway channel will also be used for hay production, resulting in a mean stem length ranging from 4 to 24 in. A grass mixture including sod-forming grasses will be used as the channel liner and will be maintained in very good to excellent condition in the interest of optimizing hay production. The spillway is to be designed to operate as a stable channel for discharges less than 500 ft^3/s.

Solution

Determination of the channel dimensions follows the outline of the preceding sections. The design discharge and channel slope are specified as:

$$Q = 500\ ft^3/s$$

$$S = 0.02\ ft/ft$$

The channel shape selected is trapezoidal with 3:1 bank slopes (Z=3). A minimum bed width of 100 ft is considered necessary if the channel is to be used for hay production.

The soil grain roughness and allowable stress are found from the relations of table 3.3 (stability outline step I-D):

$$n_s = 0.0156$$

$$C_e = 1.48-0.57\ e = 0.967$$

$$\tau_{ab} = (1.07\ I_w^2+14.3\ I_w+47.7)x10^{-4} = 0.050\ lb/ft^2$$

$$\tau_a = \tau_{ab}\ C_e^2 = 0.047\ lb/ft^2$$

The stem density for a very good stand of mixed grasses estimated using table 3.1 is (stability outline step I-B):

$$M = 4/3\ X\ 200 = 270\ stems/ft^2$$

Using the minimum anticipated stem length of 0.33 ft, the retardance curve index for stability is computed as (stability outline step I-E-1; eq. 1.3):

$$C_I = 2.5(h\sqrt{M})^{1/3} = 4.4$$

Assuming the soil boundary is relatively smooth and reasonable judgment is used in the timing of cover removal, the value of the vegetal cover factor is found from table 3.1 to be (stability outline step I-E-2):

$$C_F = 0.75$$

The allowable vegetal stress is computed as (stability outline step I-E-3, eq. 1.17):

$$\tau_{va} = 0.75\ C_I = 3.3\ \text{lb/ft}^2$$

Solving the two-dimensional flow relation for allowable unit discharge for these soil and cover conditions yields (stability outline step II-A-1-a; eq. 4.6a):

$$q = \exp\left\{\frac{-b-\sqrt{b^2-4ac}}{2a}\right\} = 4.0\ \text{ft}^3\text{/s/ft}$$

where: $a = 0.0133\ C_I = 0.0585$

$b = -(0.0954\ C_I+0.429) = -0.849$

$$c = 0.297\ C_I-0.5\ \ell n(S) +0.714\ \ell n\left\{\frac{\tau_a}{(1-C_F)n_s{}^2}\right\} -6.94 = 1.07$$

Manning's n corresponding to this discharge is computed to be (eq. 4.1a):

$$n = \exp\{C_I(0.0133[\ell n(q)]^2-0.0954\ \ell n(q)+0.297)-4.16\} = 0.036$$

The computed allowable unit discharge based on allowable vegetal stress is 39 ft^3/s/ft (stability outline step II-A-1-b; eq. 4.6d). Stability is therefore dependent on soil conditions.

The required channel width under the two-dimensional flow assumption is (stability outline step II-A-2):

$W = Q/q = 125$ ft, and the flow depth is computed as:

$$D = \left\{\frac{q\ n}{1.49\ S^{1/2}}\right\}^{0.6} = 0.80\ \text{ft}$$

Because of the large width to depth ratio (W/D=156), W may be used as the required bed width for the trapezoidal channel. Further computational refinement through the iterative solution is not justified.

The depth required to adequately carry the design flow is determined by assuming that the flow will occur when the stem length and density of the lining are at a maximum (capacity outline step I-B). The maximum value for stem length is given as:

$$h = 2.0\ \text{ft}$$

and the maximum value for stem density is estimated using table 3.1 to be:

$$M = 5/3 \times 200 = 330\ \text{stems/ft}^2$$

The retardance curve index is then:

$$C_I = 2.5(h\sqrt{M})^{1/3} = 8.3$$

Using this value of the retardance curve index and a unit discharge of 4.0 $ft^3/s/ft$ results in a computed value of Manning's coefficient of (capacity outline step II-A-2; eq. 4.6a):

$$n = \exp\{C_I(0.0133[\ell n(q)]^2 - 0.0954\ \ell n(q) + 0.297) - 4.16\} = 0.076$$

The flow depth is computed as (capacity step II-A-3):

$$D = \left\{\frac{q\ n}{1.49\ S^{1/2}}\right\}^{0.6} = 1.25\ \text{ft}$$

Again, the width to depth ratio is such that further computational refinements are not warranted. The design spillway channel has a bed width of 125 ft and a depth of 1.3 ft plus freeboard.

Example 2

As a second computational example, consider the design of a channel having the same design discharge, slope, and soil conditions as example 1. Bermudagrass is selected as the cover. The channel is to be a parabolic flood drainageway constructed through an urban park area, and the cover is to be maintained in very good condition by frequent mowing to an approximate 3-inch stem length. For maintenance reasons, the bank slope is not to be steeper than 3:1 (Z_{min}=3).

Solution

Again, the computational outline may be followed directly. The stability design parameters for this example are the same as those determined for example 1, with the exception of the cover factor and the estimated stem density which are determined from table 3.1. The parameters are:

$Q = 500\ ft^3/s$

$S = 0.02\ ft/ft$

$n_s = 0.0156$

$\tau_a = 0.047\ lb/ft^2$

$h = 0.25\ ft$

$M = 670\ stems/ft^2$

$C_I = 4.66$

$C_F = 0.90$

$\tau_{av} = 3.5\ lb/ft^2$

Solving the two-dimensional flow equations for allowable unit discharge based on soil conditions results in:

$$q = \exp\left\{\frac{-b-\sqrt{b^2-4ac}}{2a}\right\} = 12.3\ ft^3/s/ft$$

where: $a = 0.0133\ C_I = 0.0620$

$b = -(0.0954\ C_I+0.429) = -0.874$

$$c = 0.297\ C_I-0.5\ \ell n(S)+0.714\ \ell n\left\{\frac{\tau_a}{(1-C_F)n_s^2}\right\} -6.94 = 1.80$$

Manning's n is computed as (eq. 4.1a):

$$n = \exp\{C_I(0.0133[\ell n(q)]^2 - 0.0954\ \ell n(q) + 0.297) - 4.16\} = 0.030$$

The required width under the two-dimensional flow assumption is:

$$W = Q/q = 40.7 \cong 40 \text{ ft},$$

and the flow depth is:

$$D = \left\{\frac{q\ n}{1.49\ S^{1/2}}\right\}^{0.6} = 1.40 \text{ ft}$$

Continuing to follow the computational outline for stability, the parabolic channel coefficient, a_p, is estimated as:

$$a_p = \frac{2D}{W^2} = 0.00175 < \frac{1}{\sqrt{2}\ W\ Z_{min}} = 0.006$$

The mean velocity is estimated as:

$$V = q/D = 8.8 \text{ ft/s}$$

The values generated by the iterative solution described in the outline are:

Variable	Units	Iteration 1	Iteration 2	Iteration 3
A	ft^2	56.8	68.8	70.4
D	ft	1.47	1.67	1.70
R	ft	.978	1.11	1.13
n		.0319	.0322	.0323
V_m	ft/s	6.51	7.02	7.08
V	ft/s	7.27	7.10	7.09

The maximum effective stress on the soil boundary is computed as:

$$\tau_e = \gamma DS(1-C_F)(n_s/n)^2 = 0.049 \text{ lb/ft}^2$$

This computed value is close to, but greater than, the allowable value (τ_a=0.047 lb/ft^2). Strict satisfaction of the allowable stress design criterion, therefore, requires that the channel be widened by decreasing the parabolic channel coefficient. Decreasing the coefficient to:

a_p = 0.0015

and continuing the iterative solution generates the values:

Variable	Units	Iteration 4	Iteration 5
A	ft^2	70.5	72.8
D	ft	1.61	1.65
R	ft	1.07	1.10
n		.0326	.0327
V_m	ft/s	6.76	6.87
V	ft/s	6.87	6.87

The maximum effective stress on the soil boundary is now computed as:

$$\tau_e = \gamma DS(1-C_F)(n_s/n)^2 = 0.047 \text{ lb/ft}^2$$

This computed value is equal to the allowable. The stress acting on the vegetation is computed by:

$$\tau_v = \gamma DS-\tau_e = 2.0 \text{ lb/ft}^2$$

which is less than the allowable of 3.5 lb/ft^2. Channel stability design requirements are therefore satisfied.

Since the channel is to be maintained in the mowed condition, the flow depth computed for stability is also applicable for capacity considerations. The channel design is completed by the addition of desired freeboard and consideration of any special conditions or obstructions. The design parabolic channel is 66 ft wide with a bank slope of 10:1 at the design water surface (D=1.65 ft).

5. CALCULATOR- OR COMPUTER-ASSISTED DESIGN

By D.M. Temple and K.M. Robinson

The effective stress design approach discussed in the preceding chapters was intentionally developed in a format oriented toward use of the programmable calculator or computer in the design process. The degree of refinement appropriate for calculator or computer routines based on this approach will vary with individual applications and the computational hardware available. The example routines presented in this chapter are developed directly from the steady uniform flow computational outlines presented in chapter 4.

In the following sections, routines are developed specifically for the HP-97 (or HP-67) and TI-59 (or TI-58c) hand-held calculators and the IBM PC (micro-soft BASIC) desktop computer. The units were selected as commonly used representatives of those which program in reverse polish notation, algebraic notation, and the BASIC language, respectively.

TWO-DIMENSIONAL FLOW APPROXIMATION (CALCULATOR ROUTINES)

As discussed in chapter 4, the wide channel or two-dimensional flow assumption greatly simplifies the system of simultaneous equations required for allowable effective stress design of grass-lined open channels. Although never completely realized in real channel applications, this assumption may be used to obtain a reasonable estimate of required channel geometry for comparison of various combinations of soil, vegetal cover conditions, and slope, or for input to a more refined computation scheme as suggested by the stability computational outline of chapter 4.

Stability Computations

If consideration is limited to the typical design conditions for which allowable effective stress is the governing stability parameter and flow resistance may be treated as a function of unit discharge, then the maximum allowable unit discharge is a unique function (eq. 4.6a) of energy slope S, vegetal cover conditions as represented by the retardance curve index C_I and the vegetal cover factor C_F, and the soil properties of soil grain roughness n_s and allowable effective stress τ_a. Estimating these parameters for a specific design condition is discussed in chapter 3. Once the unit discharge has been determined, the corresponding flow depth may be determined using equations 4.1a and 4.10a. The mean velocity is computed as the unit discharge divided by the flow depth. If desired, these variables may be used to estimate channel cross section geometry using the relations presented in section II-B of the outline on page 58.

HP-97 and TI-59 calculator programs to compute the allowable unit discharge, flow depth, and mean velocity are presented in appendix B sections 1 and 2, respectively. Input and output for the programs are directed to the storage registers indicated in table 5.1. Input is stored in the specified registers prior to program execution, and output is extracted from the registers following program execution (the computed value of allowable discharge will be displayed at the termination of program execution). Stability computations begin at label A.

Although the programs are applicable to most practical combinations of the input variables, applicability checks should be made. The first check consists of verifying that the computed allowable unit discharge (storage register 6) is greater than the minimum required for vegetal submergence (register 17) and less than 36. Failure of the program to complete execution may also indicate a maximum allowable unit discharge outside this range. The second applicability check verifies that the allowable effective stress is the governing stability parameter. For this to be true, the computed vegetal stress (storage register 19) must be less than the allowable (storage register 9).

The computed unit discharge and corresponding depth and velocity are those that result in the computed effective stress on the soil being equal to the specified allowable stress. For some design conditions, this may not be an appropriate criterion for sizing the channel. Appropriate engineering judgment must therefore be used in applying program output as well as in determining input variables.

Capacity Computations

For the two-dimensional flow condition within the primary solution range ($0.0025\ C_I^{2.5} \leq q \leq 36$), the capacity portion of the computations consists of solving equations 4.1a and 4.10a for the flow depth. This capability is incorporated into the programs of appendix B, sections 1 and 2 beginning at label B in the programs. The registers used for variable input and output are identified in table 5.1. If stability computations were previously performed, only those variables that are to be changed need be re-stored before directing the routine to address B for continued execution. For the capacity portion of the computations, the only applicability check required is to verify that the unit discharge (input variable in register 6) is greater than the minimum value stored in register 17 but less than 36.

For channel geometries other than the two-dimensional flow approximation, both stability and capacity computations are handled in an iterative fashion as indicated in the outlines of chapter 4. Typical design problems may still be handled conveniently by programming sections III-A through III-G of the stability outline (p. 59 through 60) for the desired channel type. HP-97 and TI-59 routines are given in appendix B, sections 3 and 4 for trapezoidal channels and sections 5 and 6 for parabolic channels. I/O variables and registers are given in tables 5.2 and 5.3.

Stability Computations

In addition to the vegetal and soil parameters required for stability computations using the two-dimensional flow routines, the iterative design routines require the channel shape (bed width, B, and bank side slope, Z, for trapezoidal channels or cross-section coefficient, a_p, for parabolic channels) and the design discharge be specified. Output from the routine includes a computed value of erosionally effective stress on the soil boundary (register 18). The difference between the allowable soil stress (register 5) and the computed effective stress (register 18) is the number displayed at program termination. A positive number in the display, therefore, implies an acceptable design with respect to stability, although it may be desirable to narrow the channel if the difference is great. A negative number in the display at program termination implies an unstable design requiring the channel to be widened (B increased for a trapezoidal channel or a_p decreased for a parabolic channel). The number of trials required to obtain an acceptable channel geometry can usually be reduced by using the two-dimensional flow routine and the approximating relations of section II-B of the outline on page 58 to obtain the first estimate of the geometric control parameter.

Applicability checks for the iterative design routines are essentially the same as those required for the two-dimensional flow routines. The product of the velocity and hydraulic radius (register 16) should be checked to verify that it is between 0.0025 $C_I^{2.5}$ (register 17) and 36. If the computed vegetal stress (register 19) is greater than the allowable (register 9), then vegetal stress rather than soil stress will govern stability, and the design geometry should be adjusted accordingly.

Capacity Computations

Using the iterative design routines, the only difference in input between the stability and capacity computations is that not all the variables are required for the capacity computations (see tables 5.2 and 5.3). The variables not required to obtain the capacity flow depth are the soil parameters τ_a and n_s and the vegetal cover factor C_F. Output from the routines is the same except that stability-oriented parameters including the value in the display at the termination of execution will not have meaning to capacity computations. The only applicability check required is to verify that the product of the velocity and hydraulic radius falls in the appropriate range.

With the increased storage space normally available on computer systems, all the computations and options presented in outline form in chapter 4 may be incorporated into a single design routine or subroutine. A program listing and sample output from such a BASIC language routine (written specifically for the IBM PC desktop computer) is presented in appendix B, section 7. The routine follows the outlines of chapter 4 directly, and comments have been added to facilitate cross referencing of the variables between the program and the outlines.

Input Options

The program of appendix B, section 7 takes advantage of the flexibility of interactive computing by providing multiple input options. These include variable means of specifying the soil and cover properties, as well as the option of selecting a trapezoidal, triangular, or parabolic cross section. All input to the routine, including selection of the options, is entered from the keyboard in response to machine prompts. Output from the program is adjusted to comply with the input options chosen.

Three options are available for input of the pertinent soil properties. The first is to input the soil's classification in the unified soil classification system, followed by either the plasticity index and the void ratio or the particle diameter for which 75 percent of the material is finer. The computer will use the relations of table 3.3 to compute an allowable stress and a soil grain roughness. The second option is to input the allowable stress and soil grain roughness directly as was done for the calculator routines. The third option allows the soil to be characterized for design purposes using a bare channel permissible velocity, in which the velocity is assumed to apply to two-dimensional flow with a 3-ft flow depth.

Options available for entering the flow retardance potential of the vegetation include input of the stem length and density, direct input of the retardance curve index, and input of the Soil Conservation Service retardance classification. When the stem length and density are entered, the program will compute the retardance curve index using equation 1.3. When the SCS classification option is selected, the curve index used in computations will be that shown in table 3.2. The program assumes that the same input option used for stability will be selected for the flow retardance applicable to capacity. The vegetal cover factor applicable to stability computations is entered directly for all input options.

Output Warning Flags

Most of the available data from vegetated channels are within the primary solution range for which the calculator routines are applicable. Most practical channel designs will also fall into this category. The outlines of chapter 4 do, however, allow for channel designs in which the product of velocity and hydraulic radius is very large or very small or in which the effective stress is not the governing parameter. When this occurs, the condition should be identified so that appropriate engineering judgment may be applied.

When the BASIC language computational routine of appendix B encounters conditions for which the computed value of the VR product is outside the primary range of $0.0025\ C_I^{2.5} \leq VR \leq 36$, computations proceed with a constant value of Manning's n as indicated in the outlines of chapter 4. A flag is set within the program, however, that triggers a print statement identifying the irregularity in the computations.

For some combinations of discharge, slope, soil, and cover conditions, channel stability may not be an appropriate criterion for sizing the channel cross section. When equating the effective and allowable stresses would result in an unreasonably narrow channel, input or default minimum values of side slope or bed width are used and that fact is identified. In selecting minimum values for use in the program, remember that both the bed and banks must be able to support an adequate stand of the vegetation, and that it must be possible to construct the channel using available construction equipment and techniques.

For some combinations of slope, discharge, and cover conditions over erosion-resistant soils, the stress on the vegetation rather than the effective stress on the soil may govern channel stability. When this condition is identified by the program, the channel is sized such that the computed vegetal stress is equal to the allowable and that fact is identified in the printed output.

The relations used in the program to compute the flow resistance assume that the vegetal resistance is dominant (see discussion of eq. 1.4). For low values of the vegetal retardance curve index, this assumption becomes questionable. The printout from the routine, therefore, flags design conditions with curve index values less than 2.

In addition to the computations outlined in chapter 4, the BASIC language routine computes the Froude number for the design cross section and warns of the possibility of water surface instabilities in channels with Froude numbers very close to 1. The energy coefficient estimation relations discussed in chapter 1 (eqs. 1.8 and 1.9) are used in the Froude number calculations.

Table 5.1
1/O variable storage for calculator routines using the two-dimensional flow approximation[1]

	Variable	Definition	Unit	Storage location	Applicable to capacity	Values from example 1	
						Stability	Capacity
Input	S	Energy slope	ft/ft	1	Yes	0.02	0.02
Input	C_I	Vegetal retardance curve index	-	2	Yes	4.4	8.3
Input	C_F	Vegetal cover factor	-	3	No	.75	
Input	n_s	Soil grain roughness	-	4	No	.0156	
Input	τ_a	Allowable effective stress	lb/ft^2	5	No	.047	
Input/Output	q	Unit discharge[2]	$ft^3/s/ft$	6	Yes	4.04	4.04
Output	D	Flow depth	ft	7	Yes	.80	1.25
Output	V	Mean velocity	ft/s	8	Yes	5.05	3.24
Output	τ_{va}	Allowable vegetal stress	lb/ft^2	9	No	3.30	
Output	n	Manning's roughness coefficient	-	10	Yes	.036	.075
Output	$0.0025\ C_I^{2.5}$		ft^2/s	17	Yes	.102	.496
Output	τ_v	Vegetal stress	lb/ft^2	19	No	.951	

[1]Applies to routines of appendix B, sections 1 and 2. Input is stored in specified registers prior to execution. Output must be recalled from registers following execution. Example problem statement is given in chapter 4, p. 65.

[2]Unit discharge is an output variable to the stability routine beginning at label A and an input variable to the capacity routine beginning at label B.

Table 5.2
1/0 variable storage for iterative design calculator routines for trapezoidal channels[1]

	Variable	Definition	Unit	Storage location	Applicable to capacity	Values from example 1	
						Stability	Capacity
Input	S	Energy slope	ft/ft	1	Yes	0.02	0.02
Input	C_I	Vegetal retardance curve index	-	2	Yes	4.4	8.3
Input	C_F	Vegetal cover factor	-	3	No	.75	
Input	n_s	Soil grain roughness	-	4	No	.0156	
Input	τ_a	Allowable effective stress	lb/ft^2	5	No	.047	
Input	Q	Volumetric discharge	ft^3/s	6	Yes	500	500
Input	B	Channel bed width	ft	7	Yes	125	125
Input	Z	Cotangent of bank side slope	-	8	Yes	3	3
Output	τ_{va}	Allowable vegetal stress	lb/ft^2	9	No	3.30	
Output	A	Cross-sectional area	ft^2	10	Yes	102	162
Output	R	Hydraulic radius	ft	11	Yes	.783	1.22
Output	n	Manning's roughness coefficient	-	12	Yes	.0364	.0781
Output	D	Flow depth	ft	13	Yes	.799	1.26
Output	V	Mean velocity	ft/s	14	Yes	4.91	3.08
Output	T	Channel width at water surface	ft	15	Yes	130	133
Output	VR	Velocity x Hydraulic radius	ft^2/s	16	Yes	3.84	3.76
Output	$0.0025\ C_I^{2.5}$		ft^2/s	17	Yes	.102	.496
Output	τ_e	Effective stress	lb/ft^2	18	No	.0457	
Output	τ_v	Vegetal stress	lb/ft^2	19	No	.951	

[1]Applies to routines of appendix B, sections 3 and 4. Input is stored in specified registers prior to execution. Output must be recalled from registers following execution. Example problem statement is given in chapter 4, p. 65.

Table 5.3
1/0 variable storage for iterative design calculator routines for parabolic channels[1]

	Variable	Definition	Unit	Storage location	Applicable to capacity	Values from example 2	
						Stability	Capacity
Input	S	Energy slope	ft/ft	1	Yes	0.02	0.02
Input	C_I	Vegetal retardance curve index	-	2	Yes	4.66	4.66
Input	C_F	Vegetal cover factor	-	3	No	.90	
Input	n_s	Soil grain roughness	-	4	No	.0156	
Input	τ_a	Allowable effective stress	lb/ft^2	5	No	.047	
Input	Q	Volumetric discharge	ft^3/s	6	Yes	500	500
Input	a_p	Parabolic cross section coefficient	1/ft	7	Yes	.0015	.0015
Output	τ_{va}	Allowable vegetal stress	lb/ft^2	9	No	3.50	
Output	A	Cross-sectional area	ft^2	10	Yes	72.9	72.9
Output	R	Hydraulic radius	ft	11	Yes	1.10	1.10
Output	n	Manning's roughness coefficient	-	12	Yes	.0327	.0327
Output	D	Flow depth	ft	13	Yes	1.65	1.65
Output	V	Mean velocity	ft/s	14	Yes	6.86	6.86
Output	T	Channel width at water surface	ft	15	Yes	66.3	66.3
Output	VR	Velocity x Hydraulic radius	ft^2/s	16	Yes	7.53	7.53
Output	$0.0025\ C_I^{2.5}$		ft^2/s	17	Yes	.117	.117
Output	τ_e	Effective stress	lb/ft^2	18	No	.0469	
Output	τ_v	Vegetal stress	lb/ft^2	19	No	2.01	

[1]Applies to routines of appendix B, sections 5 and 6. Input is stored in specified registers prior to execution. Output must be recalled from registers following execution. Example problem statement is given in chapter 4, p. 68.

6. GRAPHICAL DESIGN OF OPEN CHANNELS

By K.M. Robinson and D.M. Temple

The iterative channel design procedure discussed and applied in chapters 4 and 5 can be depicted graphically by a series of nomographs. The graphical solutions presented in this chapter were constructed to allow the user to rapidly estimate stable channel design parameters for trapezoidal and parabolic channel sections. In contrast to the numerical design procedures, the nomographs require only a few simple computations to complete the stability and capacity designs.

GRAPHICAL DESIGN PROCEDURE

The nomographs are intended for use in conjunction with the permissible velocity curves of SCS (1977). The bare channel reference velocity is the basic velocity for sediment-free flow in a wide (two-dimensional flow) unlined channel flowing 3 ft deep. Vegetal parameters (stem density and cover factor) can be estimated from the grass properties shown in Table 3.1. After obtaining the stem density, the retardance curve index C_I may be determined using the stem length-stem density nomograph (fig. 6.1) or equation 1.3. The curve index values plotted on the nomographs (10, 7.64, 5.60, 4.44, and 2.88) were selected because of their equivalence to the retardance classes previously used by the Soil Conservation Service (SCS, 1954) (see table 3.2).

Stability Design

The sediment-free basic velocity curves of SCS (1977) are reproduced as figures 6.2 and 6.3 for convenient application. The grain size for discrete (cohesionless) particles or the plasticity index and void ratio for coherent (cohesive) materials are required as input parameters. The void ratio correction curve (fig. 3.2, reproduced as figure 6.4 for convenience of application) is used with the coherent material basic velocity chart (fig. 6.3). Other corrections such as alignment and frequency as discussed by SCS (1977) are application-specific and require the user's discretion.

The channel slope and the basic velocity associated with the soil are input variables for the unit discharge nomographs (figs. 6.5 through 6.29). These 25 charts result from 5 cover factors (0.9, 0.87, 0.75, 0.50, and 0.25) for each of 5 values of the curve index. These charts provide a unit discharge (q) which satisfies stability requirements under the wide-channel assumption.

The unit discharge and channel slope are then used as input variables for the wide-channel depth nomographs (figs. 6.30 through 6.34). These five nomographs represent each curve index (retardance class) and provide a flow depth D for the specified slope and cover conditions. The nomographs may also be used to obtain a capacity flow depth in channels satisfying the two-dimensional flow assumption.

Once the unit discharge and depth are determined with the design discharge known, the geometric control parameter for a specific channel section can be calculated. The equations in table 6.1 assume the controlling width is at one-half depth. Also, from the wide-channel assumption the width is equal to the design discharge divided by the unit discharge (that is, $W=Q/q$). The equations for calculating the geometric control parameters for trapezoidal and parabolic channels are shown in table 6.1. Once the geometric control parameter is determined, channel geometry is fixed and the stability portion of the design is complete, provided the vegetation has not been overstressed.

The designer should verify that the vegetal stress imposed by the flow is less than the allowable vegetal stress. For the range of variables depicted by the nomographs, this check can be simplified to the following expression:

$$\gamma DS < 0.75\ C_I$$

where γ = unit weight of water (62.4 lb/ft^3),
D = depth of flow (ft),
S = channel slope (ft/ft), and
C_I = retardance curve index.

Capacity Design

The capacity design determines the increased channel depth necessary to carry the required discharge at the maximum anticipated vegetal retardance. The geometric control parameter (B or a_p), along with the design discharge and channel slope, are input parameters for the capacity nomographs. The parabolic channel nomographs (figs. 6.35 through 6.38) provide solutions for curve index values of 10, 7.64, 5.60, and 4.44, respectively. The trapezoidal channel nomographs (figs. 6.39 through 6.62) provide solutions for the same curve index values at side slopes of 2, 3, 4, 5, 6, and 10, respectively. The design is completed by adding an appropriate freeboard to the flow depth obtained from the nomographs. Table 6.2 lists all these figures by type and figure number and by page number for ease of reference.

LIMITATIONS

The nomographs are graphical representations of multivariable functions that are subject to specific limitations. The nomographs are applicable for designing trapezoidal and parabolic channels within the limits of the plotted scales. The scales were plotted to provide a trade-off between computational precision and range and should not be extrapolated.

The geometric control parameter established from stability design is determined graphically using the wide channel assumption (two-dimensional flow) as described in chapter 4. The nomographic solutions in comparison to the numerical solutions are most often, but not always, conservative.

The comparison of nomographic and numerical solutions is discussed in more detail by Robinson and Temple (1986). Usually, however, differences in design due to computational simplifications will be less than the differences caused by estimating and discretizing the design parameters.

The user must also be aware that stability may not be the limiting factor, thereby causing the nomograph to provide solutions that may be unreasonable in such terms as balancing cut and fill quantities, matching available construction equipment, and crossing with farm machinery. The nomographs cannot replace sound engineering judgment.

The nomographic solutions available are limited to the discrete values of curve indexes and cover factors presented. Because of the interaction of multiple variables, interpolation of results between two charts is not recommended. Intermediate values of C_I and C_F should normally be represented by the next lower values to determine channel stability and the next higher value for capacity.

The nomographs, read with reasonable care, will provide solutions with reasonable accuracy. This graphical design procedure, while subject to limitations, does provide a rapid solution technique for users without computers and programmable calculators.

EXAMPLE DESIGN

The example problems used in chapters 4 and 5 are used to illustrate application of the curves and nomographs of this chapter.

<u>Example 1</u>

The problem statement for example 1 is presented in chapter 4 on page 65. The "given" information may be summarized as:

Vegetation	
type	grass mixture (very good to excellent condition)
stem length	$0.33 \leq h \leq 2$ ft
Soil	
classification	CL
plasticity index	$I_w = 15$
void ratio	$e = 0.9$
Channel	
shape	trapezoidal
side slope	3:1
minimum bed width	100 ft
bed slope	2 percent
design discharge	500 ft^3/s

Solution

The charts needed for design may be located using table 6.2 beginning on page 88.

<u>Stability design</u>. From table 3.1, p. 44: The cover factor (C_F) for the grass mixture is 0.75, and the stem density is estimated as $270 \leq M \leq 330$ stems/ft^2.

From fig. 6.1, p. 91: A 0.33-ft cover with a density of 270 stems/ft^2 has a class D retardance ($C_I \cong 4.44$).

From fig. 6.3, p. 92: A CL soil with an I_w of 15 indicates the basic velocity is 3.2 ft/s.

From fig. 6.4, p. 93: The void ratio correction factor (C_e) resulting from CL material with a void ratio of 0.9 is 0.97.

Therefore, the adjusted basic velocity is (3.2 x 0.97) = 3.1 ft/s.

For stability design at a $C_I = 4.44$ and $C_F = 0.75$ the appropriate unit discharge nomograph is identified from table 6.2 as figure 6.12.

From fig. 6.12, p. 97: Drawing a straight line through an adjusted basic velocity of 3.1 ft/s and a channel slope S of 2 percent allows the unit discharge q to be read as 4.0 $ft^3/s/ft$.

Table 6.2 identifies the appropriate wide-channel depth nomograph as figure 6.33.

From fig. 6.33, p. 108: Drawing a line through S = 2 percent and q = 4.0 $ft^3/s/ft$ allows the wide-channel depth D to be read as 0.80 ft.

The equation in table 6.1, p. 87, allows calculation of the required bed width, B.

For a trapezoidal channel:

$$B = (Q/q) - ZD = (500/4) - (3)(0.8) = 122.6 \cong 125 \text{ ft}$$

Verify that the vegetal stress is less than the allowable vegetal stress.

$$\gamma DS < 0.75\ C_I$$

$$(62.4)(0.8)(0.02) < (0.75)(4.44)$$

$$1.0 < 3.3$$

<u>Capacity design</u>. From fig. 6.1, p. 91: A 2-ft cover with a density of 330 stems/ft^2 has a retardance curve index of C_I = 8.3, which is between a class A and B retardance. Therefore, capacity design is based on a class A retardance (C_I = 10).

From table 6.2, the nomograph applicable for capacity design is figure 6.43. This chart is found not to apply, however, because the design width is outside the range of the chart. The design depth is therefore estimated under the wide channel assumption using figure 6.30. Entering the chart with a unit discharge of 4 $ft^3/s/ft$ and a slope of 2 percent yields a design flow depth of 1.5 ft.

Before adding freeboard, the channel design may be summarized as:

Shape	Channel bed width B, ft	Capacity depth D, ft	Cross-sectional area[1] A, ft^2	Top width[2] T, ft	Side slope Z
Trapezoidal	125	1.5	194	134	3

[1] $A = D(B+ZD)$
[2] $T = B+2ZD$

<u>Example 2</u>

The problem statement for example 2 is given in chapter 4, p. 68. The "given" information may be summarized as:

Vegetation	
type	bermudagrass (very good stand)
stem length	$h = 0.25$ ft
Soil	
classification	CL
plasticity index	$I_w = 15$
void ratio	$e = 0.9$
Channel	
shape	parabolic
maximum side slope	3:1
bed slope	2 percent
design discharge	500 ft^3/s

Solution

Again, table 6.2 is used to locate the needed charts.

<u>Stability design</u>. From table 3.1, p. 44: The cover factor (C_F) for bermudagrass is 0.90, and the stem density is estimated at 670 stems/ft^2.

From fig. 6.1, p. 91: A 0.25-ft cover with a density of 670 stems/ft^2 has a retardance curve index of 4.7, which is between a class C and D retardance. Stability design is therefore based on a class D retardance.

Soil conditions are the same as for example 1, resulting in an adjusted basic velocity of 3.1 ft/s.

From fig. 6.14, p. 98: The allowable unit discharge corresponding to a basic velocity of 3.1 ft/s and a slope of 2 percent is 11.3 $ft^3/s/ft$.

From fig. 6.33, p. 108: The wide channel depth is 1.3 ft.

From table 6.1, p. 87: The parbolic channel geometric control parameter is computed as:

$$a_p = (2Dq^2)/Q^2 = (2)(1.3)(11.3)^2/(500)^2 = 0.0013$$

Verify that the vegetal stress is less than the allowable vegetal stress.

$$\gamma DS < 0.75\ C_I$$

$$(62.4)(1.3)(0.02) < (0.75)(4.44)$$

$$1.6 < 3.3\ \ lb/ft^2$$

Capacity design. Because the retardance potential of the cover is between a class C and D retardance, a class C retardance should be assumed for capacity design. The appropriate design chart found in table 6.2 is figure 6.37.

From fig. 6.37, p. 110: Entering the chart with $a_p = 0.0013$, $Q = 500$, and $S = 2$ percent, yields a design flow depth of 1.7 ft.

Before adding freeboard, the channel design may be summarized as:

Shape	Channel coefficient[1] a_p	Capacity depth D, ft	Cross-sectional area[2] A, ft^2	Top width[3] T, ft	Side slope[4] Z
Parabolic	0.0013	1.7	82	72	10.7

[1] $a_p = D/(T/2)^2$
[2] $A = D^{3/2}/(0.75\sqrt{a_p})$
[3] $T = 2\sqrt{D/a_p}$
[4] $Z = 1/(a_p T)$

The channel can be widened and/or deepened to allow construction to an even dimension; however, the channel coefficient a_p should not be increased.

Table 6.1
Geometric control parameters

Channel type	Geometric control parameter	Determining equation
Trapezoidal	Bed width, B	$B = (Q/q)-ZD$
Parabolic	Channel coefficient, a_p	$a_p = (2Dq^2)/Q^2$

where B = bed width (ft),

Z = side slope,

a_p = parabolic channel coefficient (1/ft), $D = a_p(T/2)^2$,

Q = design discharge (ft^3/s),

q = unit discharge ($ft^3/s/ft$),

D = channel flow depth (ft), and

T = channel width at water surface (ft).

Table 6.2
Chart index

Grass properties table			Table 3.1, p. 44
Geometric control parameters			Table 6.1, p. 87
Stem length-stem density nomograph			Fig. 6.1, p. 91
Basic velocity curve (discrete material)			Fig. 6.2, p. 92
Basic velocity curve (coherent material)			Fig. 6.3, p. 92
Void ratio correction curve			Fig. 6.4, p. 93
Allowable unit discharge nomographs			
	C_I = 2.88 (E)	C_F = 0.25	Fig. 6.5, p. 94
		C_F = 0.50	Fig. 6.6, p. 94
		C_F = 0.75	Fig. 6.7, p. 95
		C_F = 0.87	Fig. 6.8, p. 95
		C_F = 0.90	Fig. 6.9, p. 96
	C_I = 4.44 (D)	C_F = 0.25	Fig. 6.10, p. 96
		C_F = 0.50	Fig. 6.11, p. 97
		C_F = 0.75	Fig. 6.12, p. 97
		C_F = 0.87	Fig. 6.13, p. 98
		C_F = 0.90	Fig. 6.14, p. 98
	C_I = 5.60 (C)	C_F = 0.25	Fig. 6.15, p. 99
		C_F = 0.50	Fig. 6.16, p. 99
		C_F = 0.75	Fig. 6.17, p. 100
		C_F = 0.87	Fig. 6.18, p. 100
		C_F = 0.90	Fig. 6.19, p. 101
	C_I = 7.64 (B)	C_F = 0.25	Fig. 6.20, p. 101
		C_F = 0.50	Fig. 6.21, p. 102
		C_F = 0.75	Fig. 6.22, p. 102
		C_F = 0.87	Fig. 6.23, p. 103
		C_F = 0.90	Fig. 6.24, p. 103

Table 6.2 --Continued
Chart index

Table 6.2 --Continued
Chart index

Trapezoidal channel capacity nomographs--Continued		
	C_I = 10.0 (A)	Fig. 6.47, p. 115
Z = 4:1	C_I = 7.64 (B)	Fig. 6.48, p. 115
	C_I = 5.60 (C)	Fig. 6.49, p. 116
	C_I = 4.44 (D)	Fig. 6.50, p. 116
	C_I = 10.0 (A)	Fig. 6.51, p. 117
Z = 5:1	C_I = 7.64 (B)	Fig. 6.52, p. 117
	C_I = 5.60 (C)	Fig. 6.53, p. 118
	C_I = 4.44 (D)	Fig. 6.54, p. 118
	C_I = 10.0 (A)	Fig. 6.55, p. 119
Z = 6:1	C_I = 7.64 (B)	Fig. 6.56, p. 119
	C_I = 5.60 (C)	Fig. 6.57, p. 120
	C_I = 4.44 (D)	Fig. 6.58, p. 120
	C_I = 10.0 (A)	Fig. 6.59, p. 121
Z = 10.1	C_I = 7.64 (B)	Fig. 6.60, p. 121
	C_I = 5.60 (C)	Fig. 6.61, p. 122
	C_I = 4.44 (D)	Fig. 6.62, p. 122

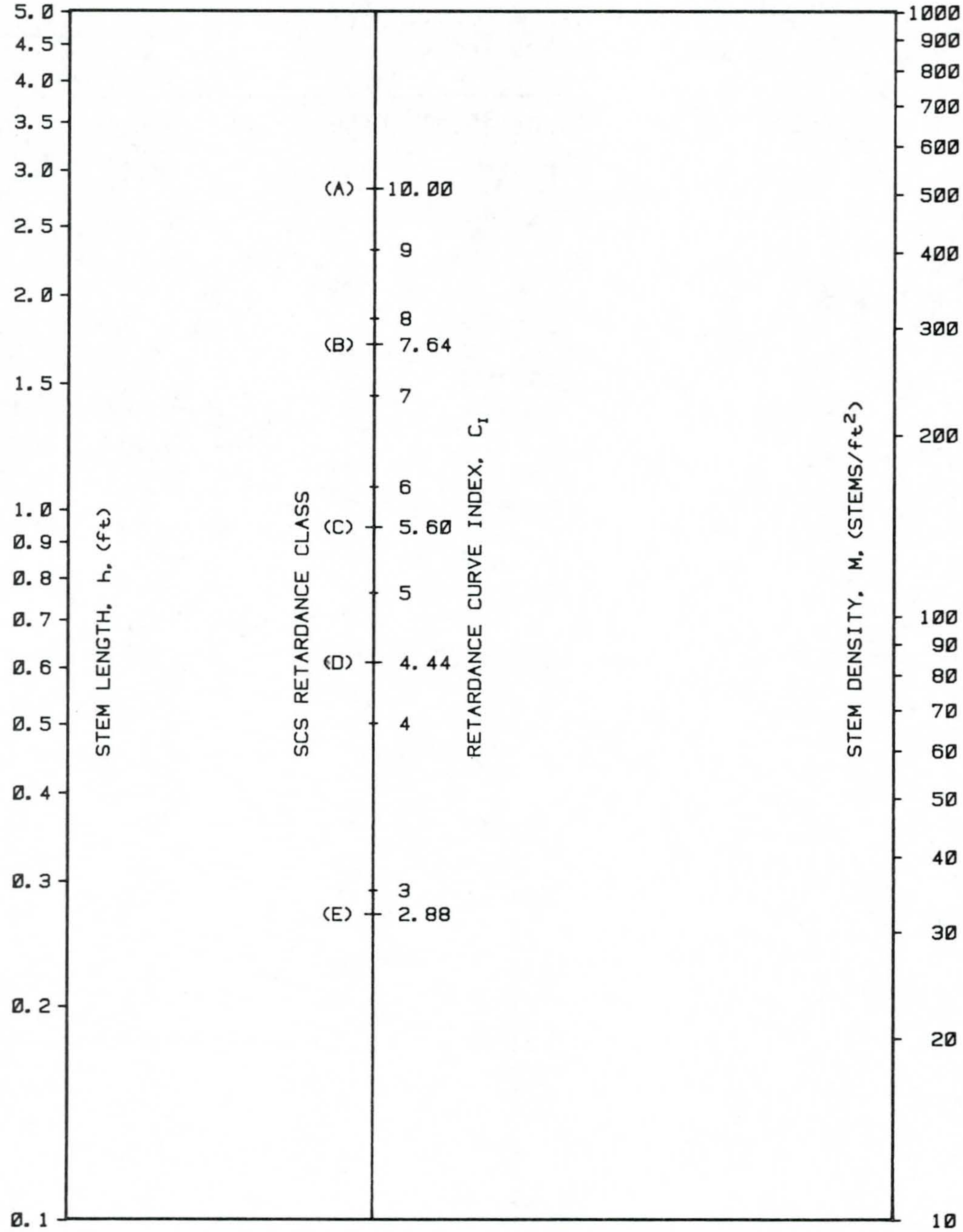


Figure 6.1
Stem length-stem density nomograph.

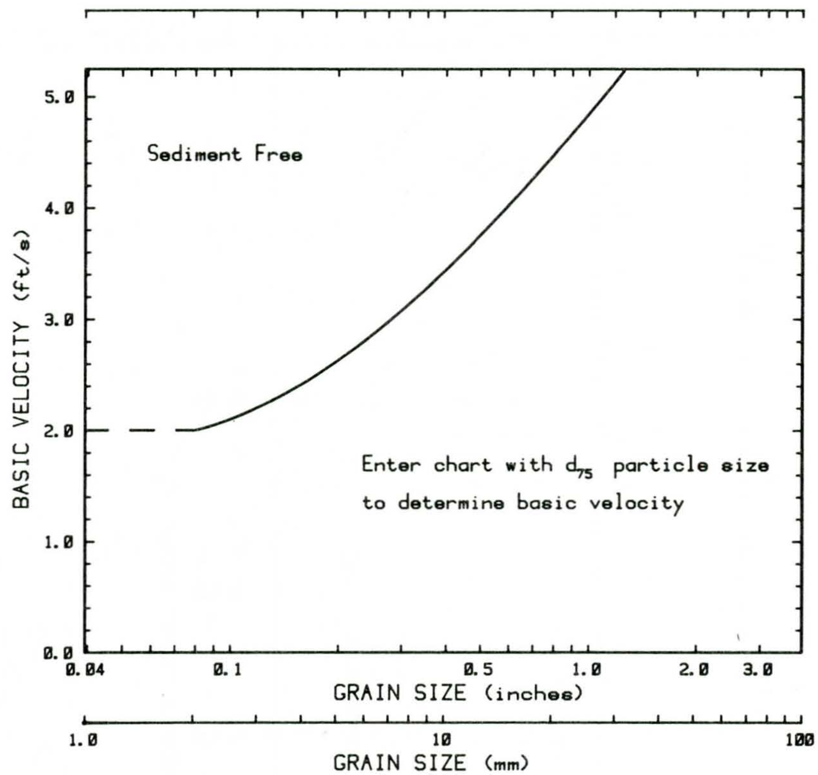


Figure 6.2
Basic velocity curve (discrete material).

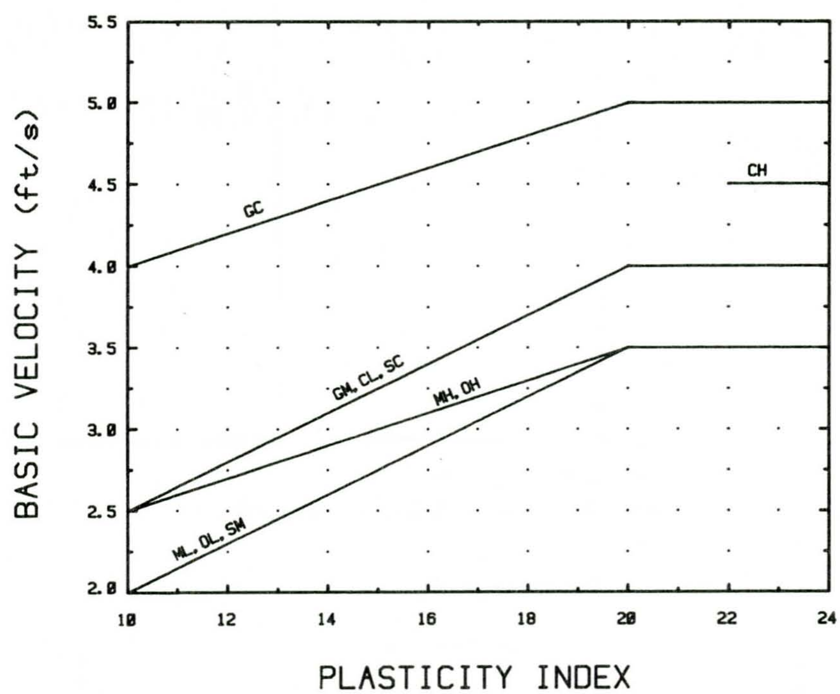


Figure 6.3
Basic velocity curve (coherent material).

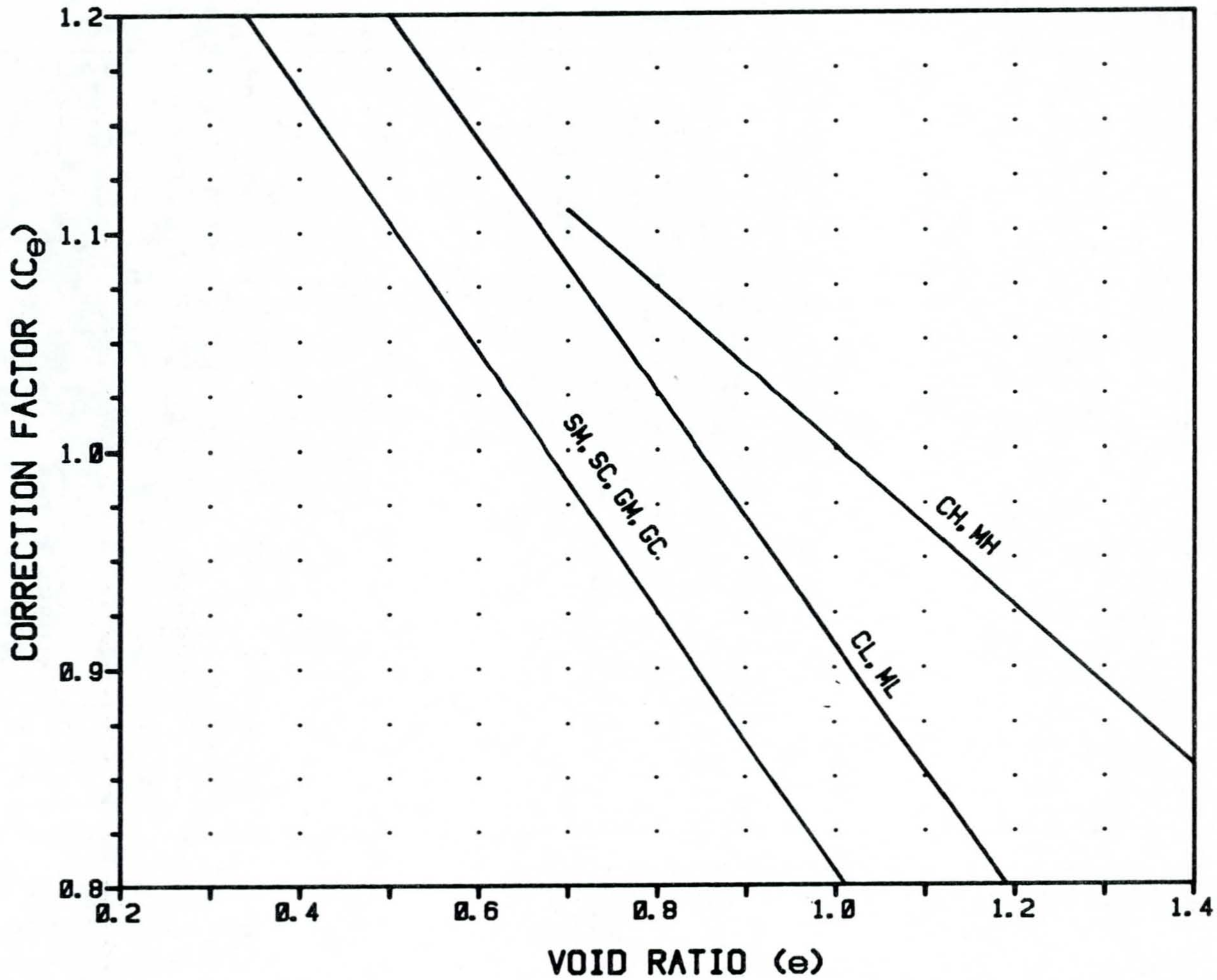


Figure 6.4
Void ration correction curve.

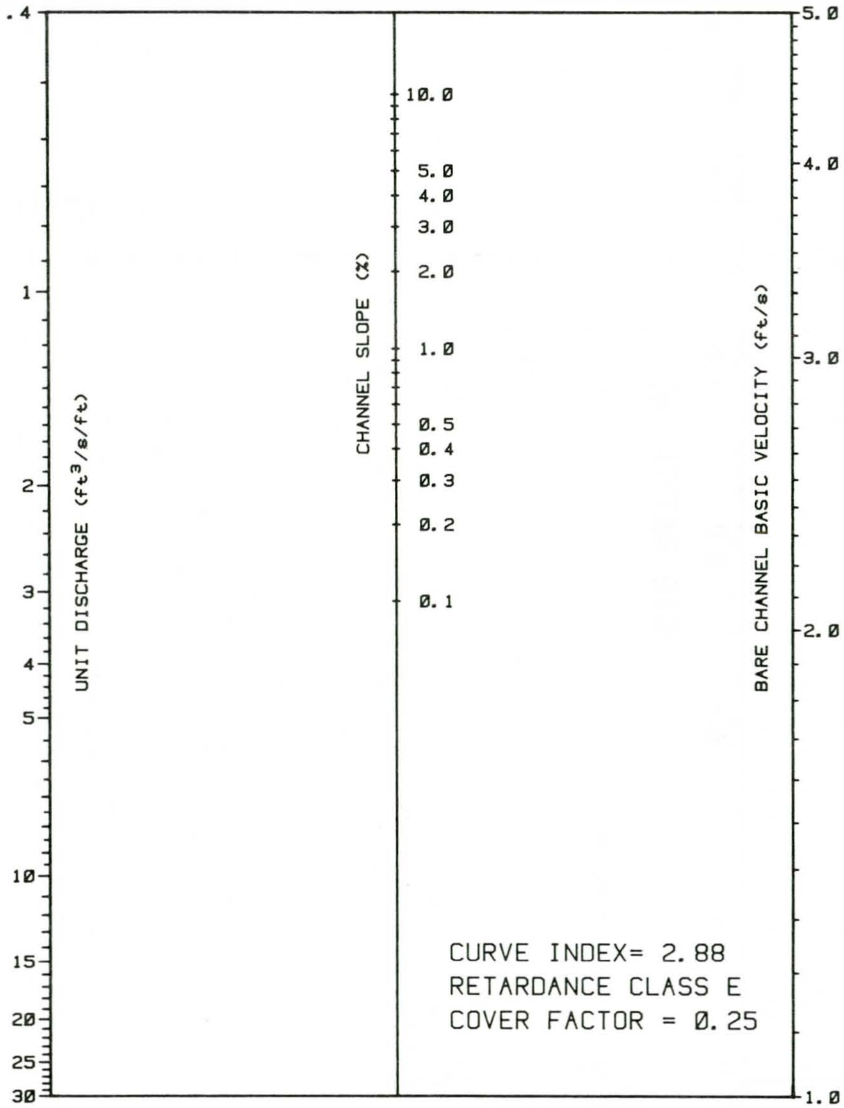


Figure 6.5

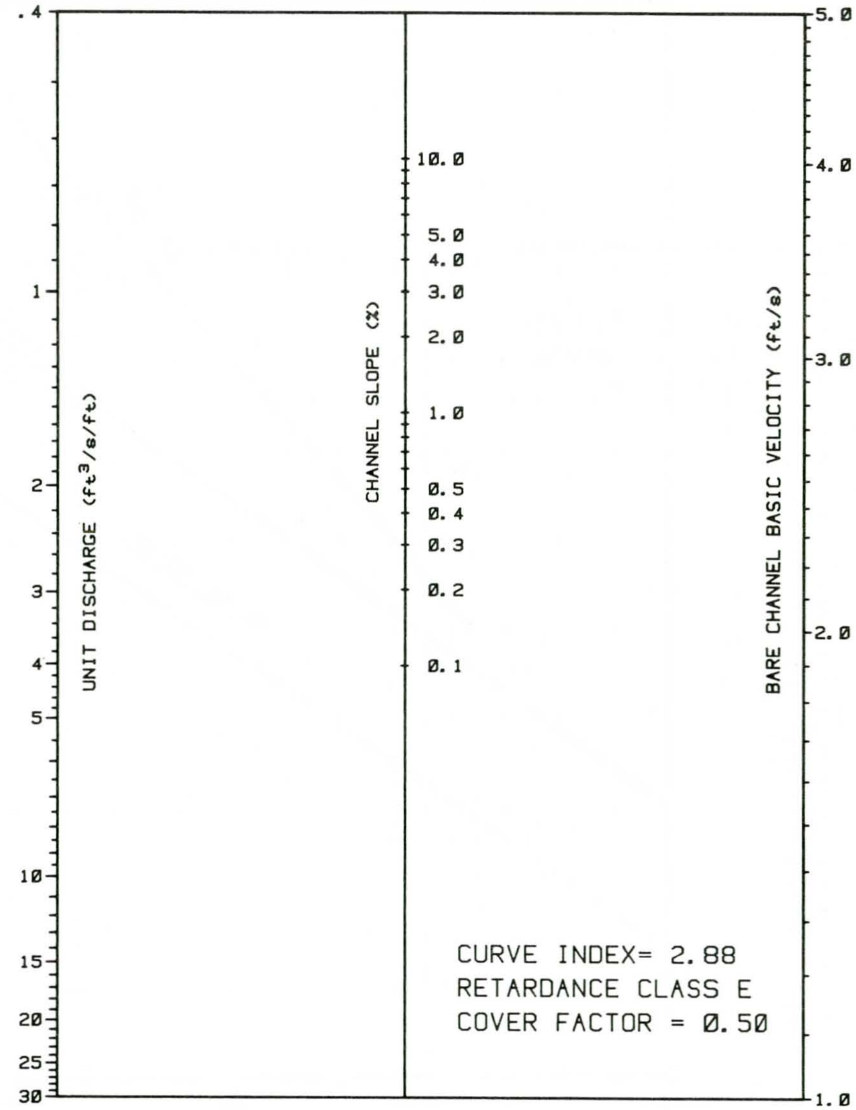


Figure 6.6

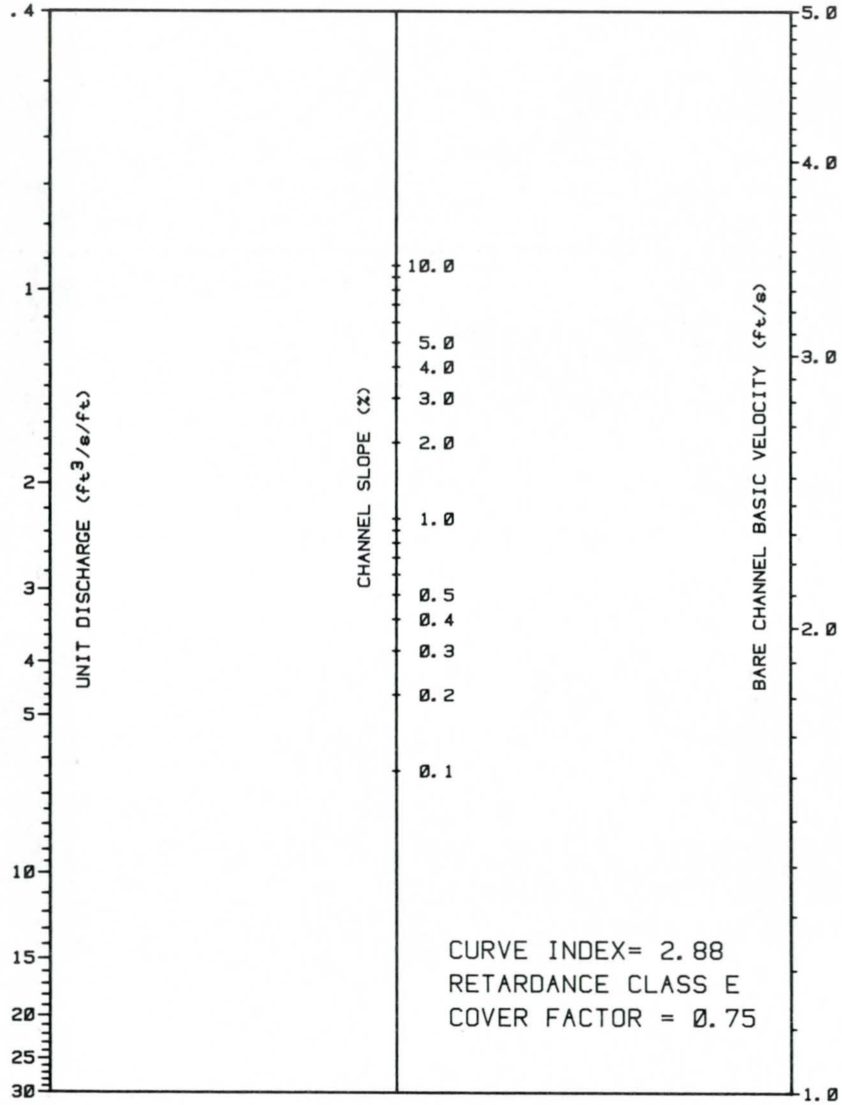


Figure 6.7

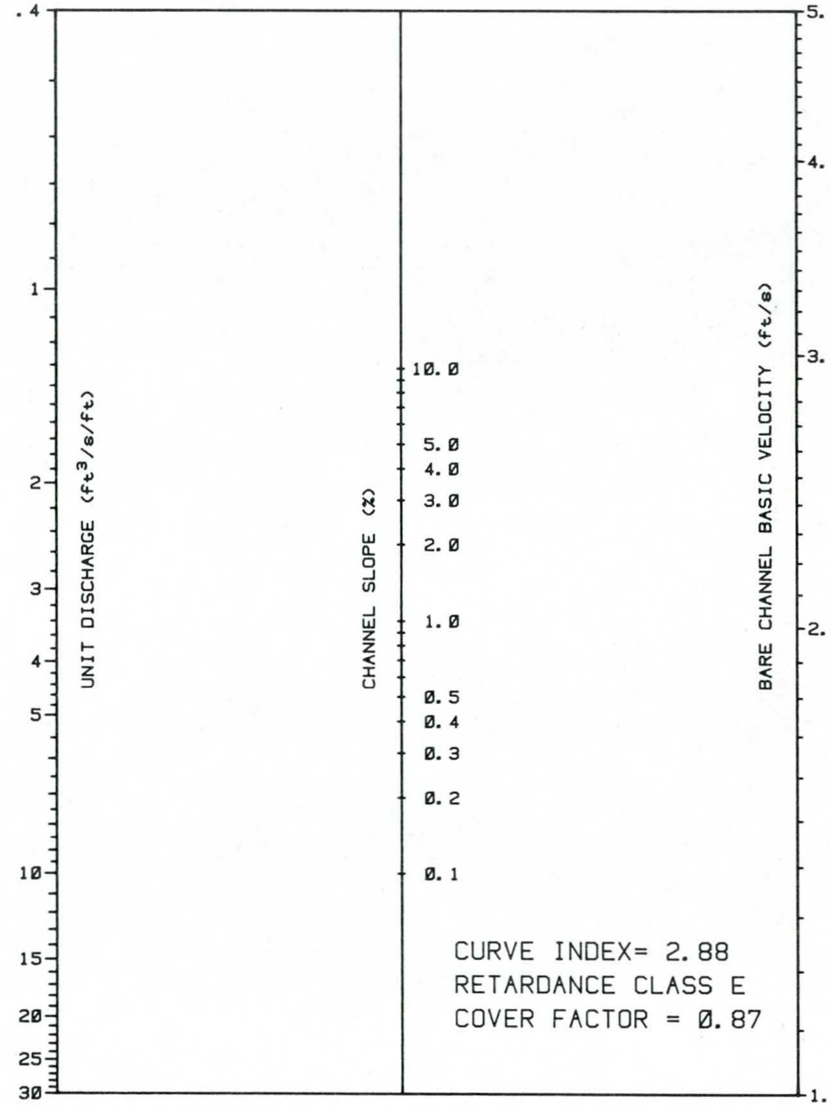


Figure 6.8

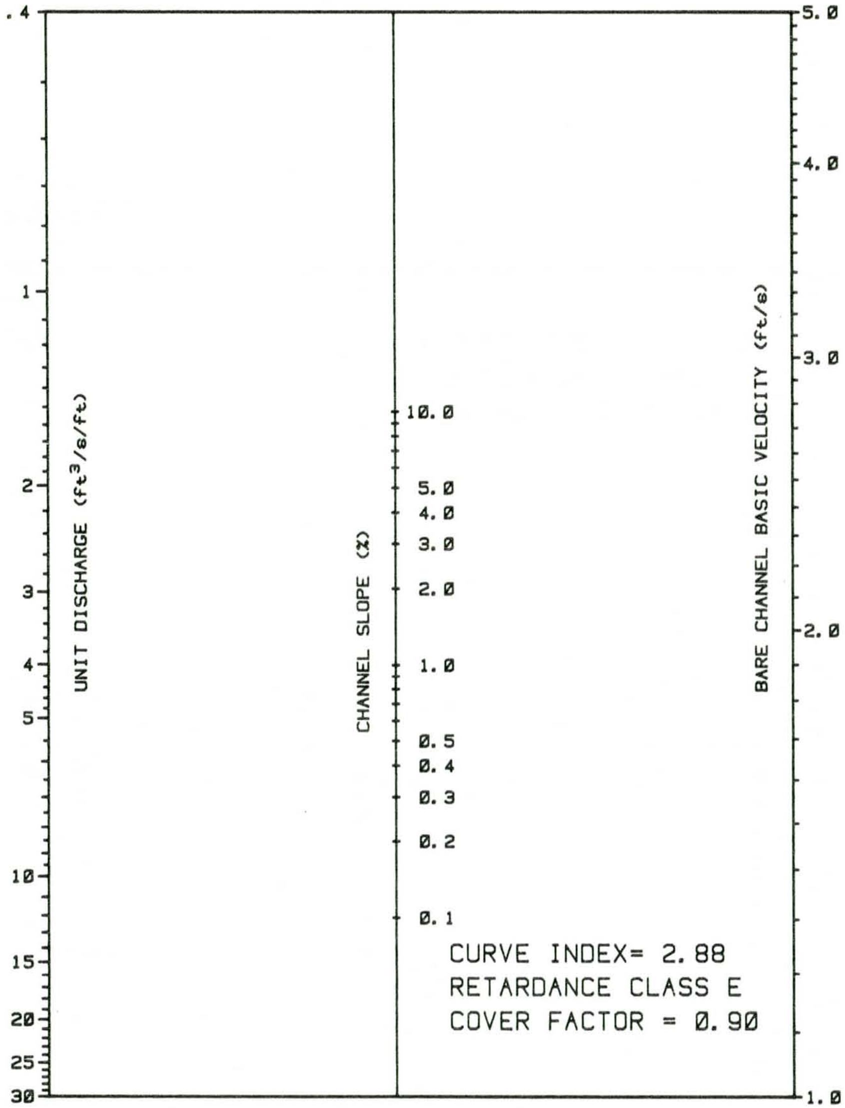
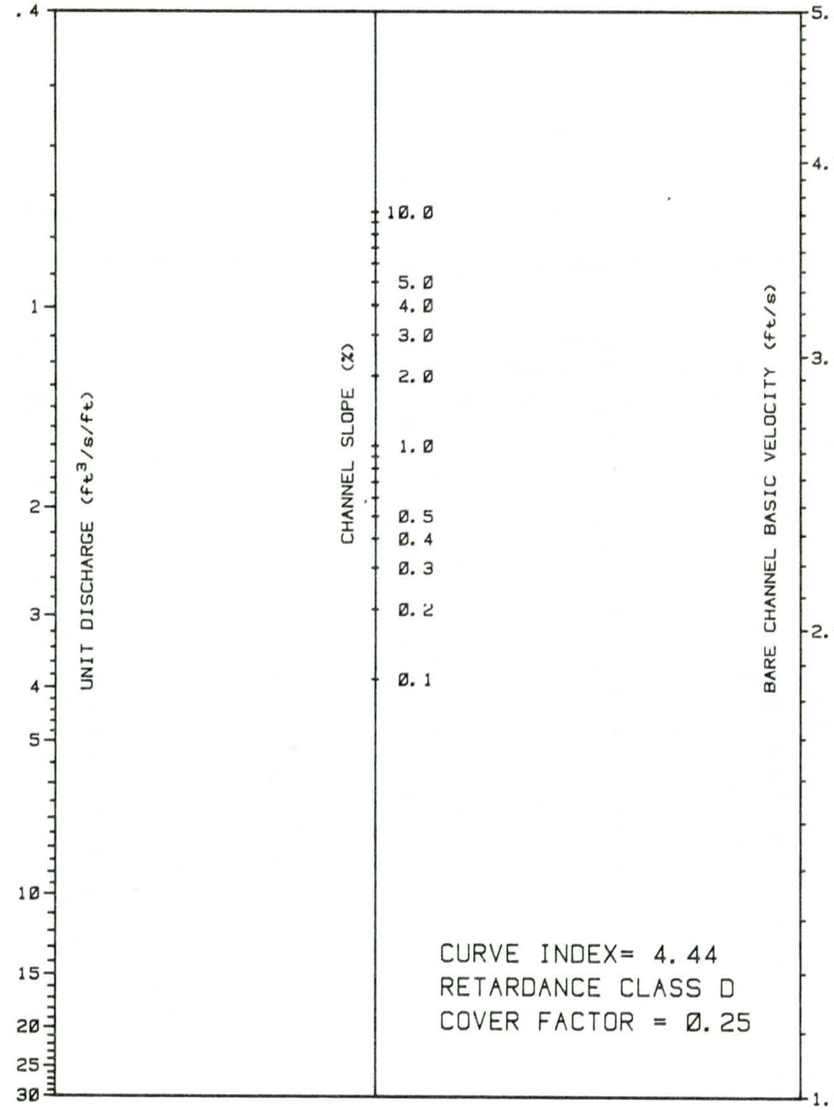


Figure 6.9



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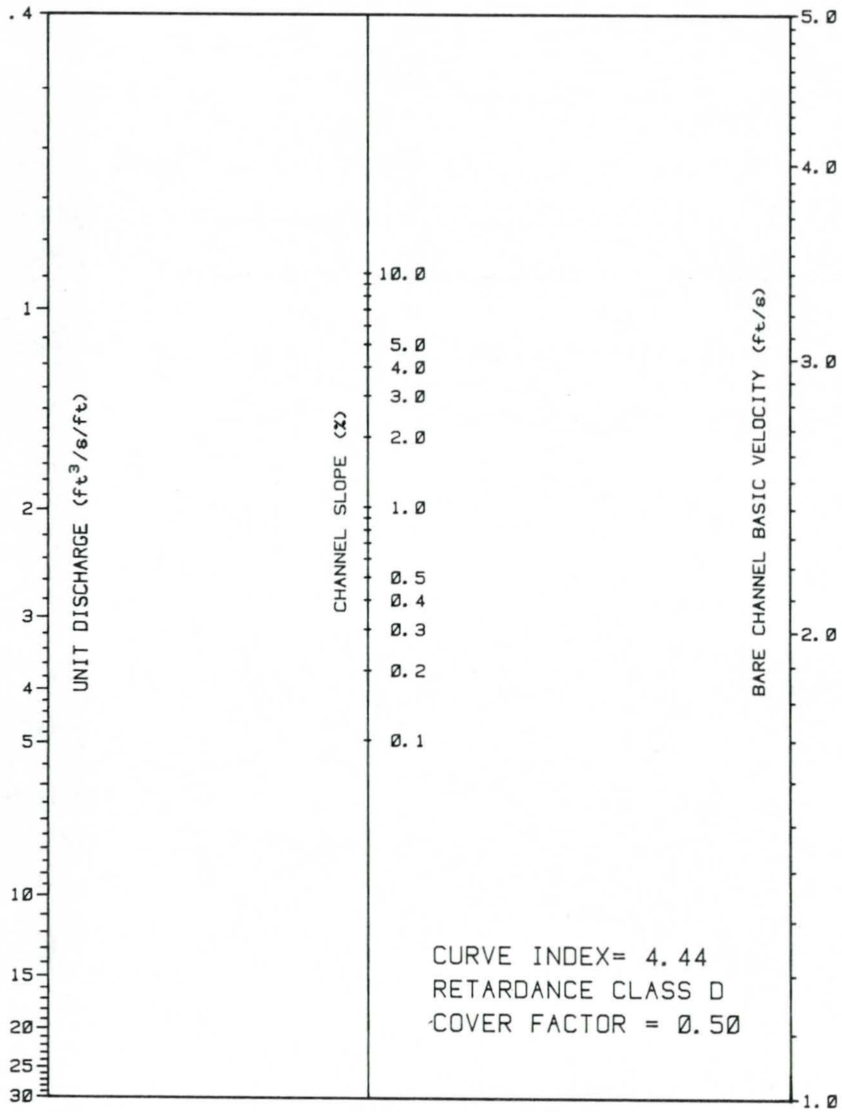

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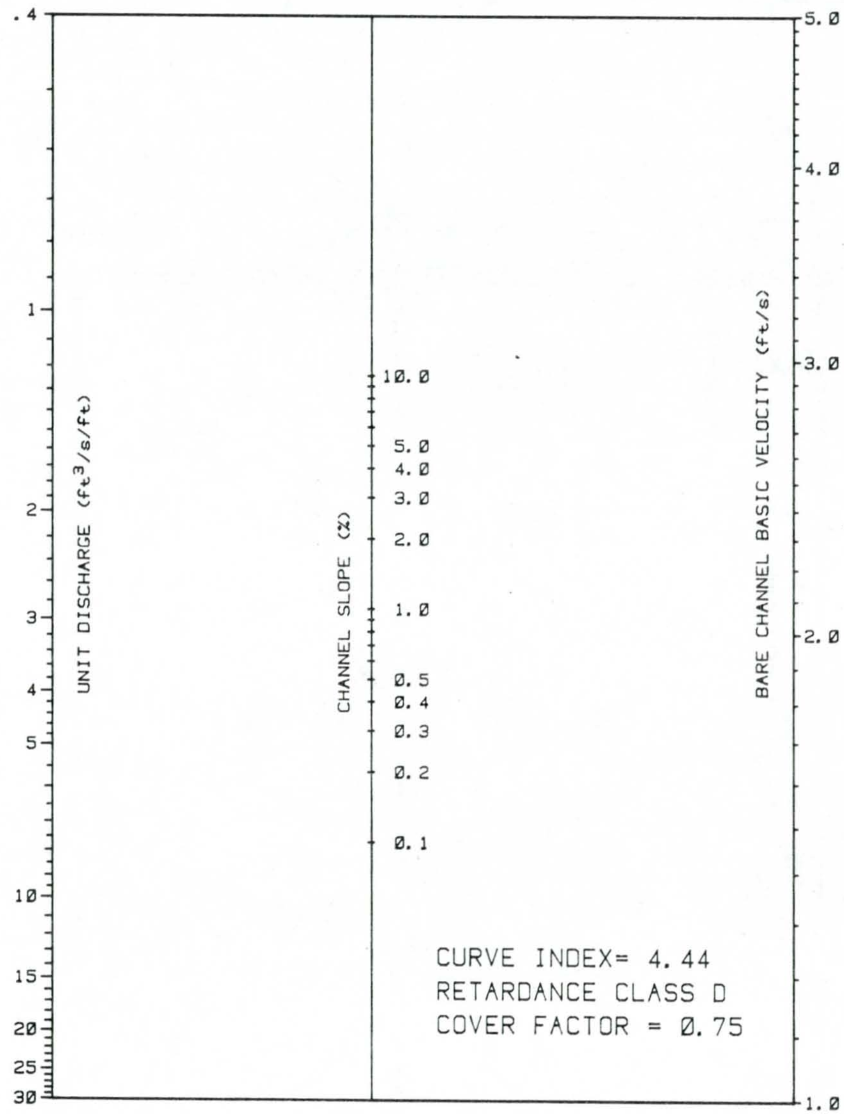

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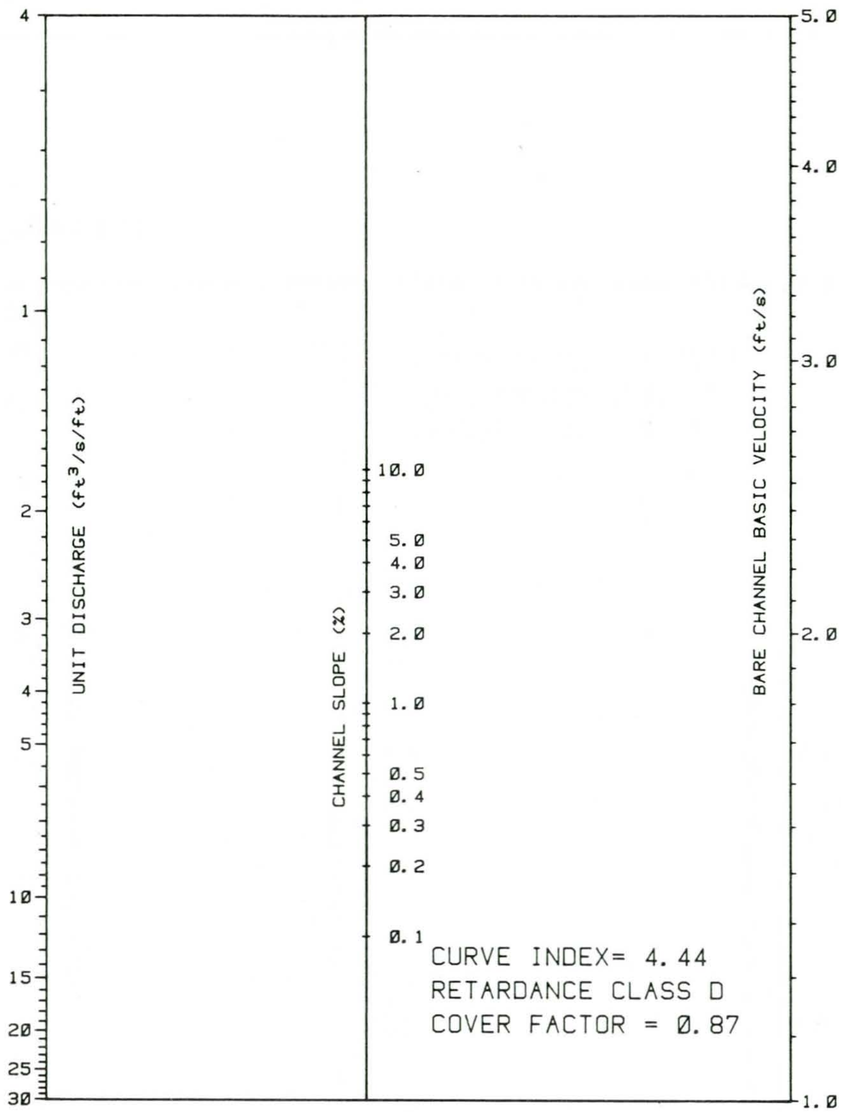

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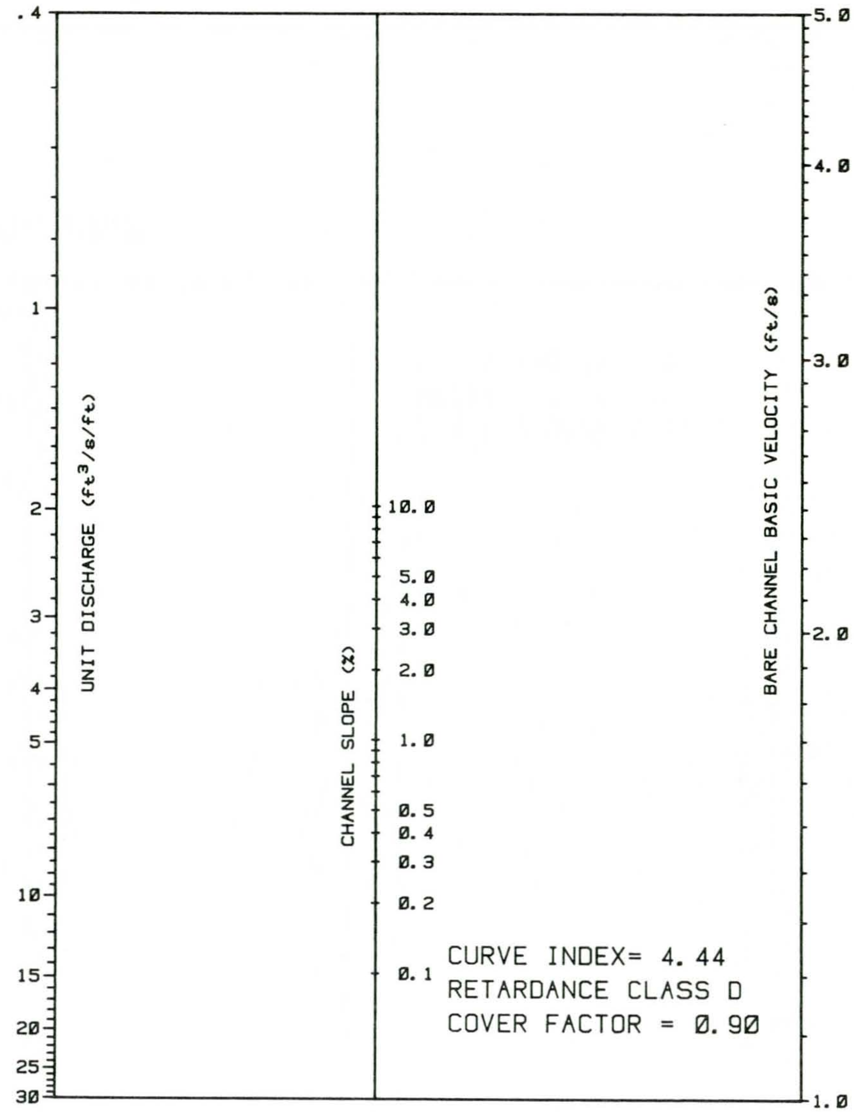

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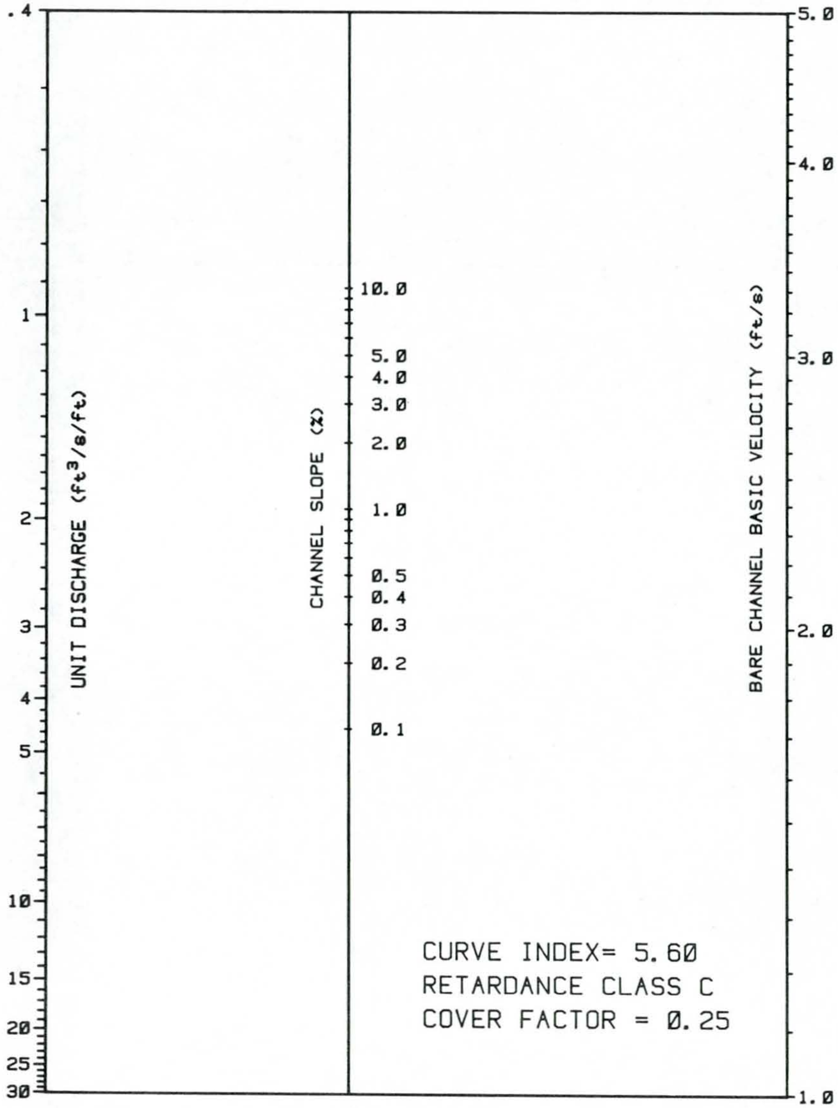

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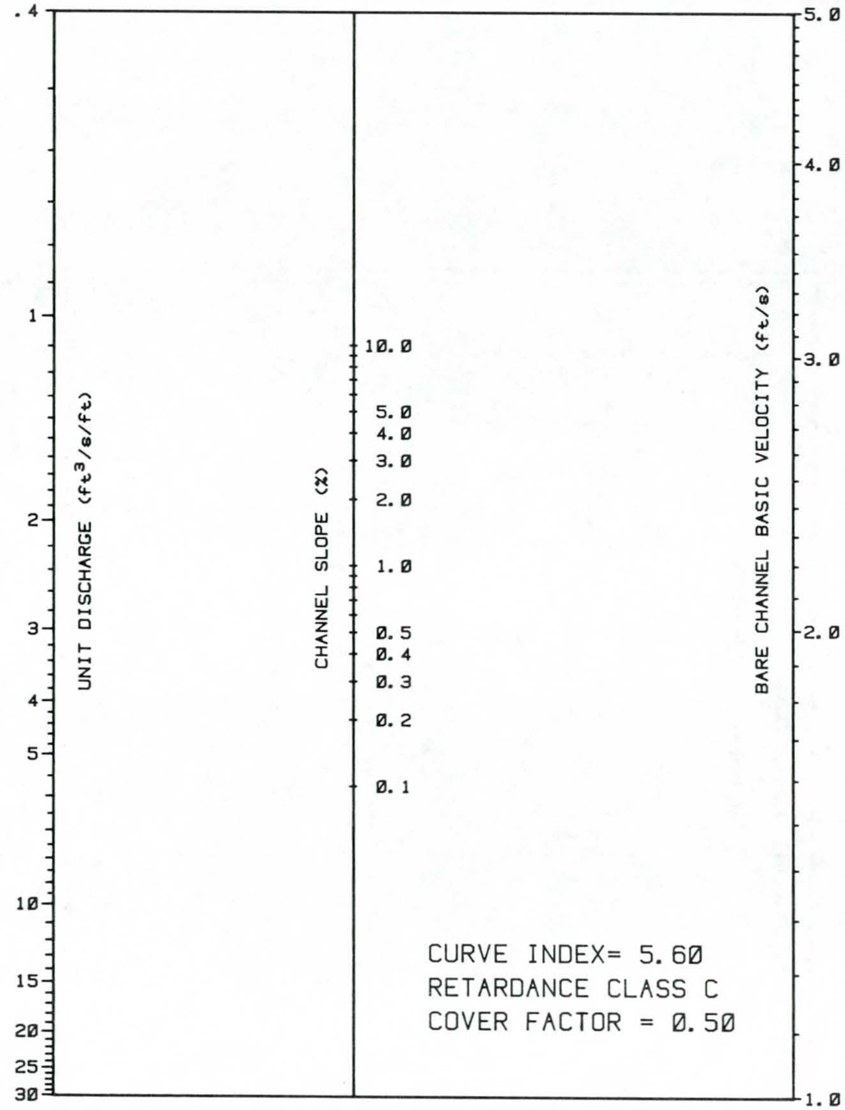

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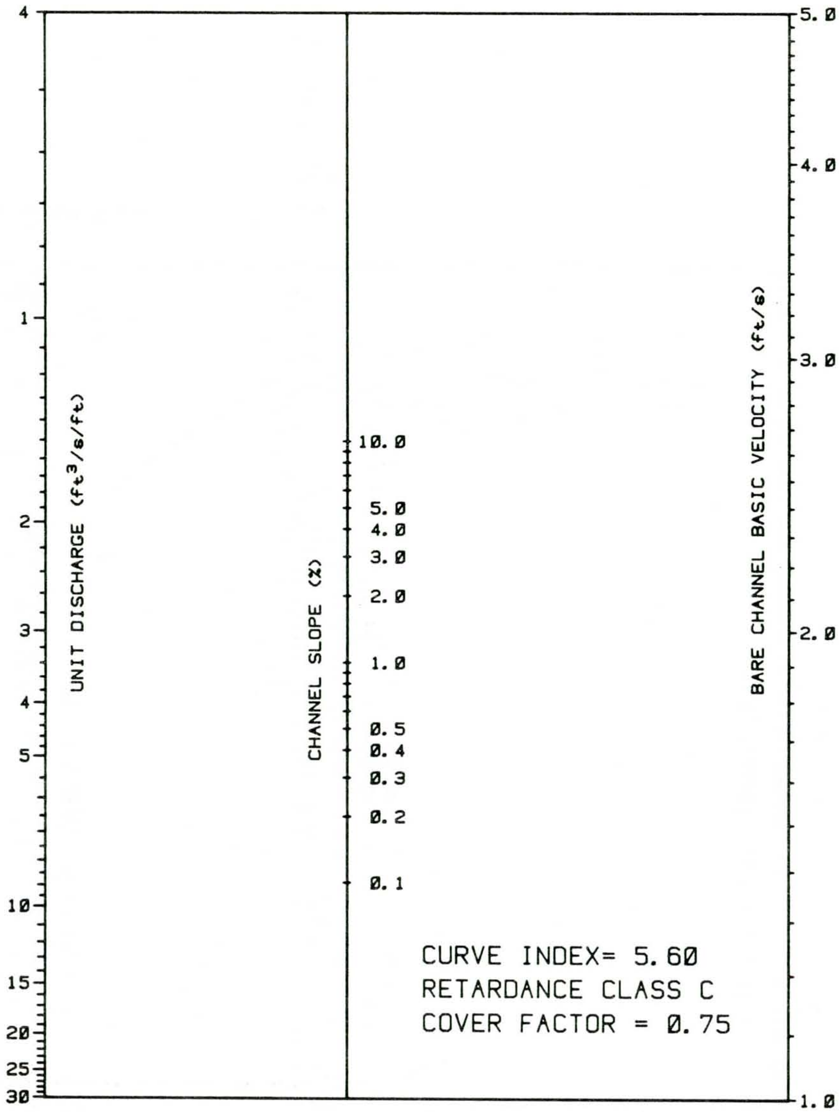

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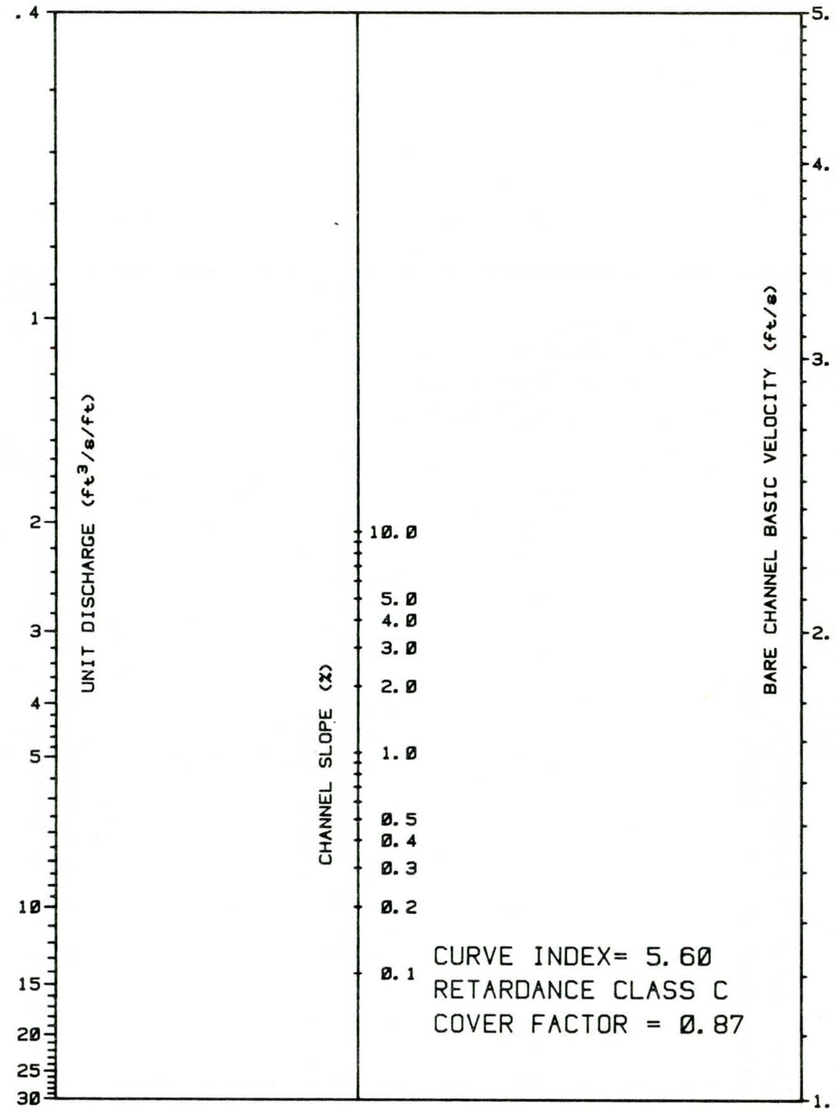

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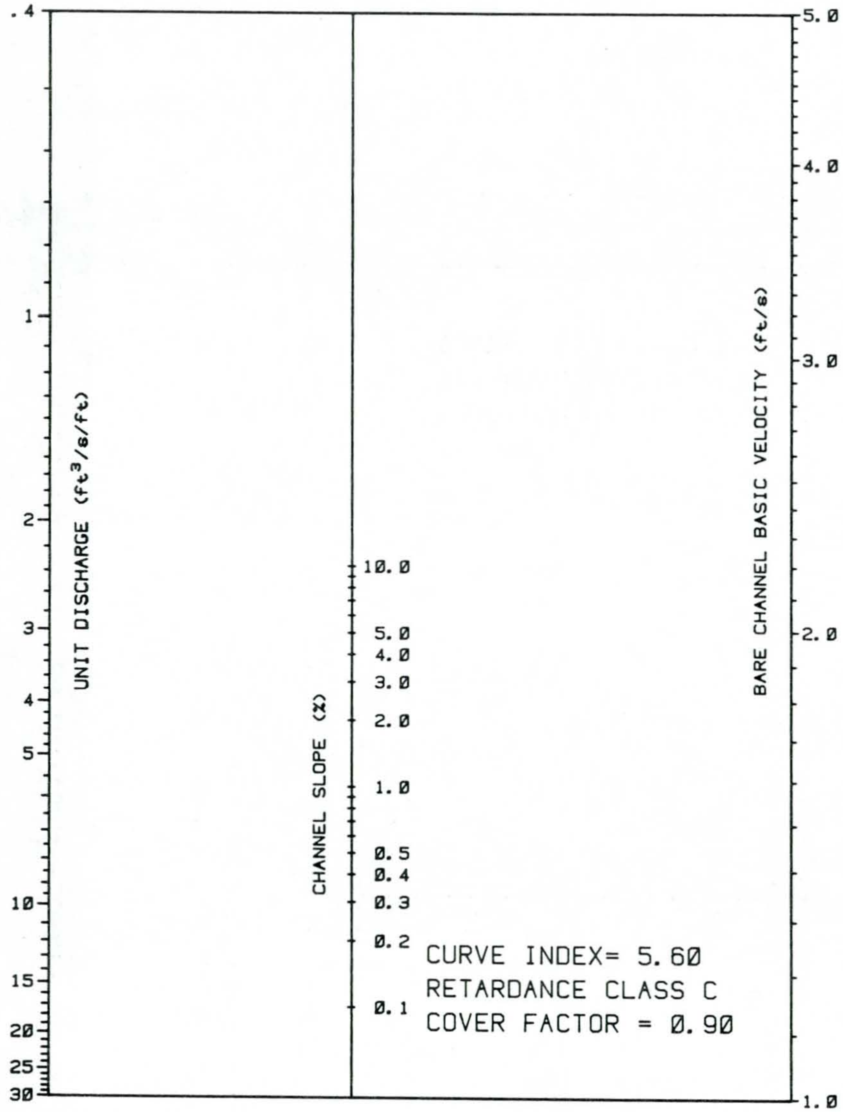

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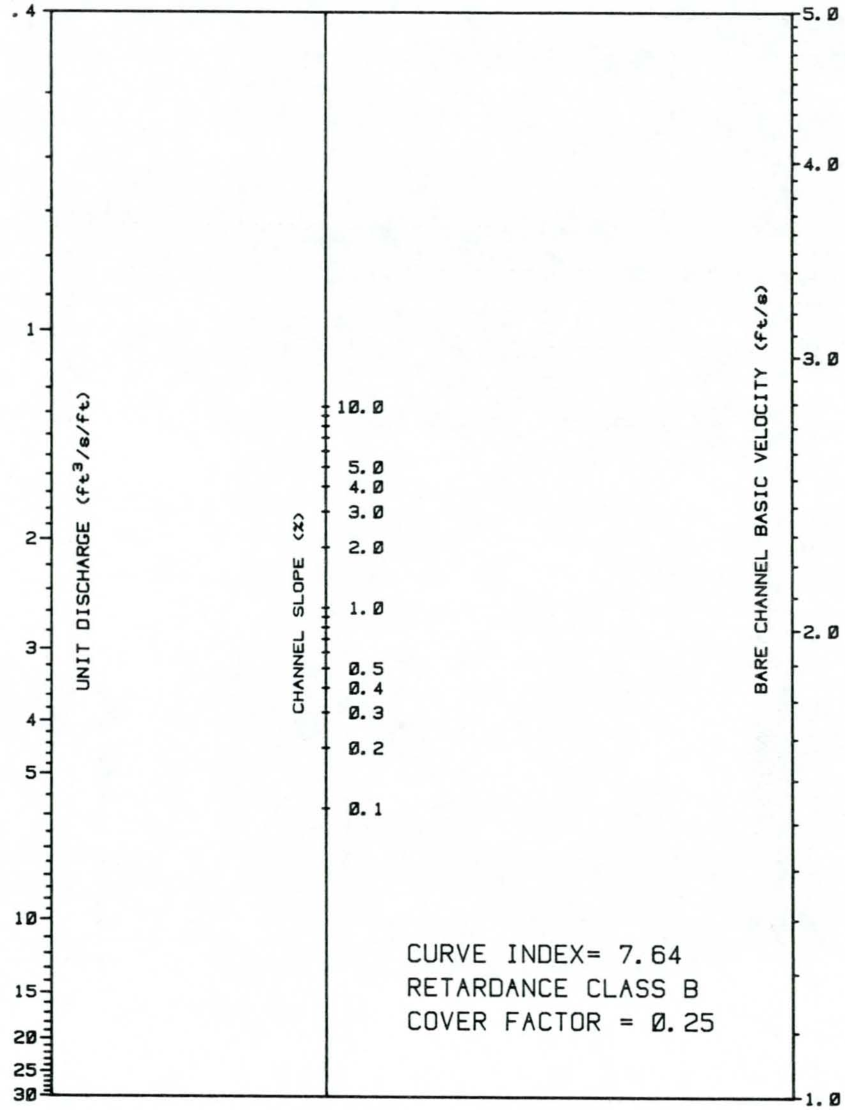

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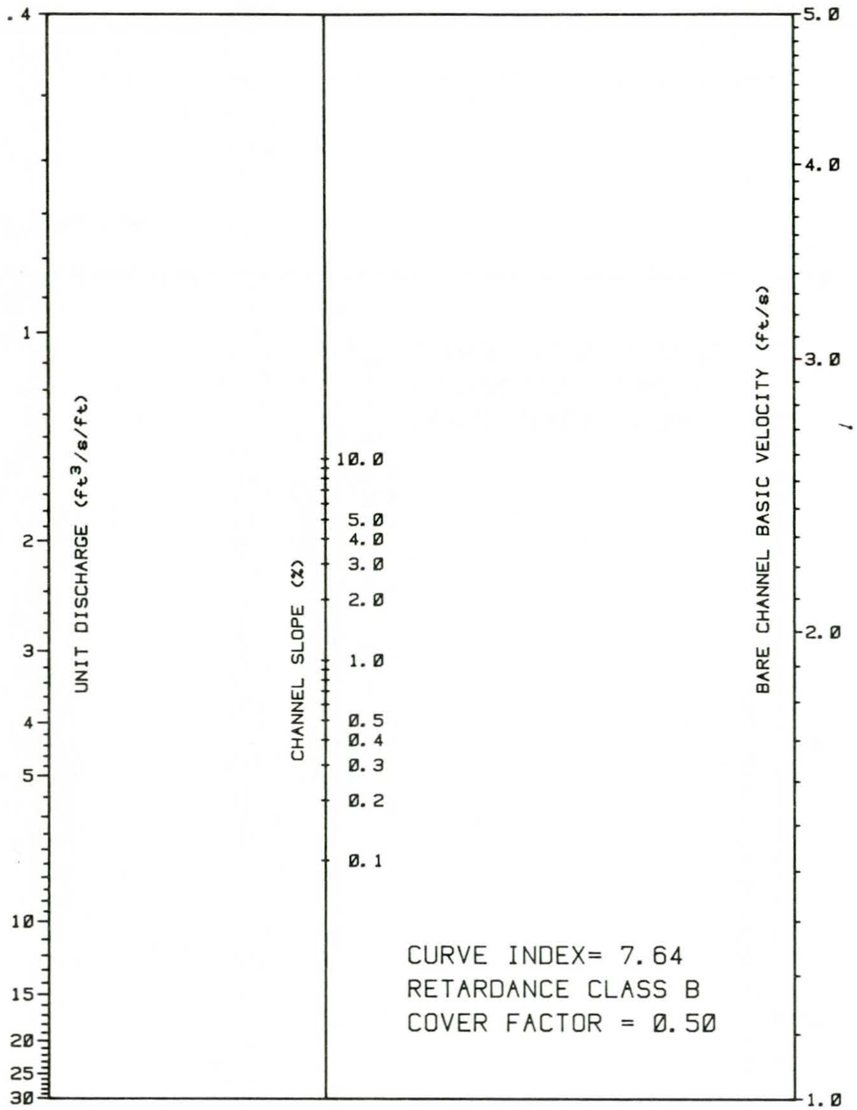

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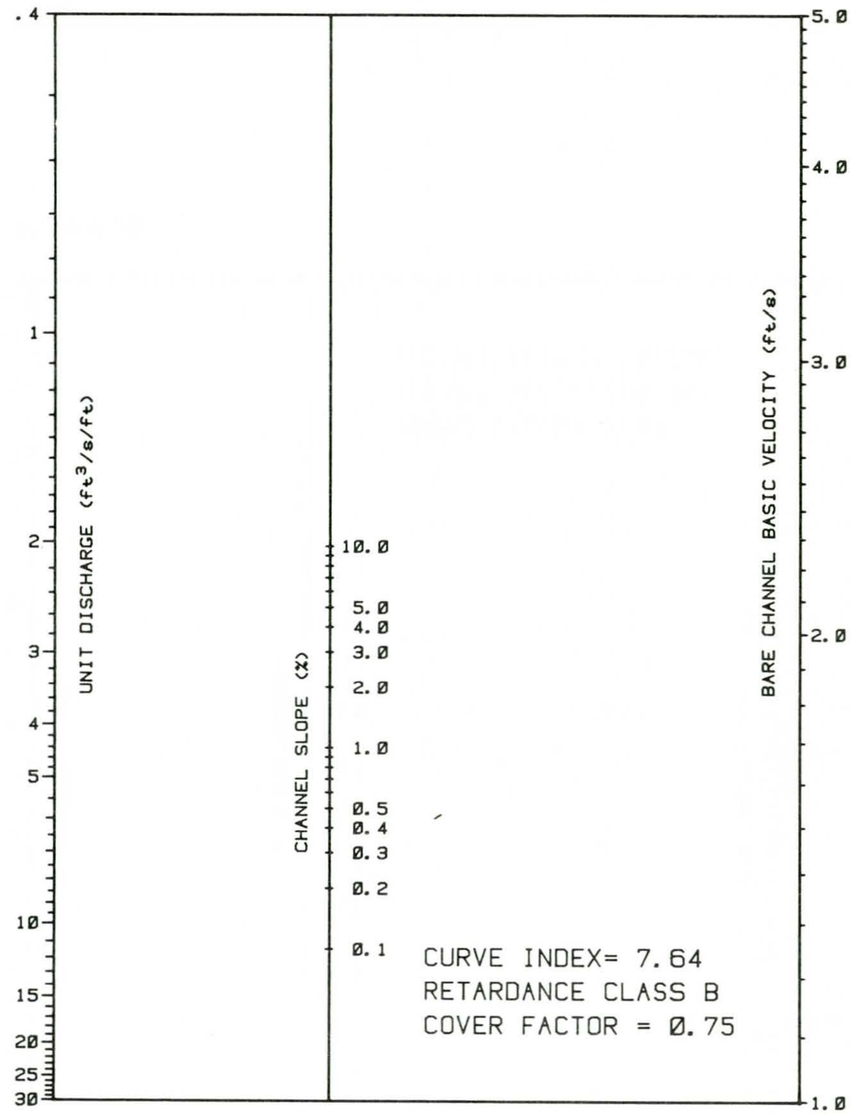

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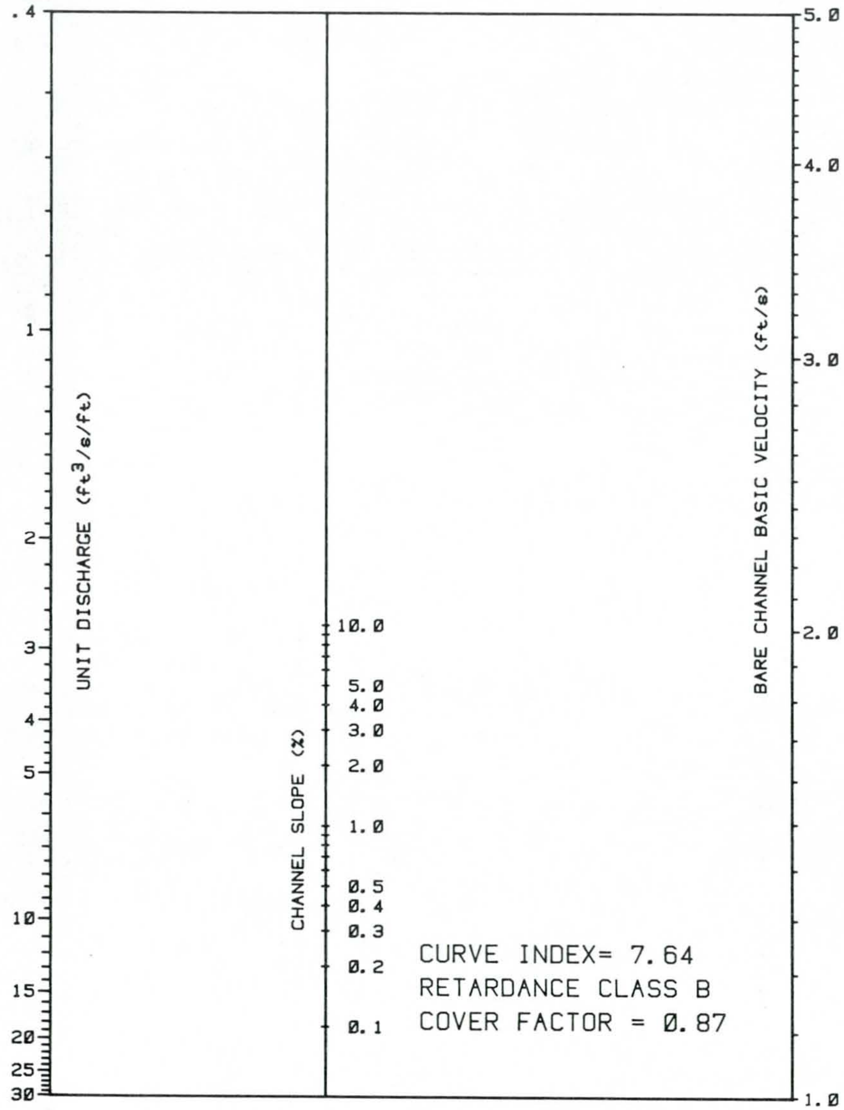

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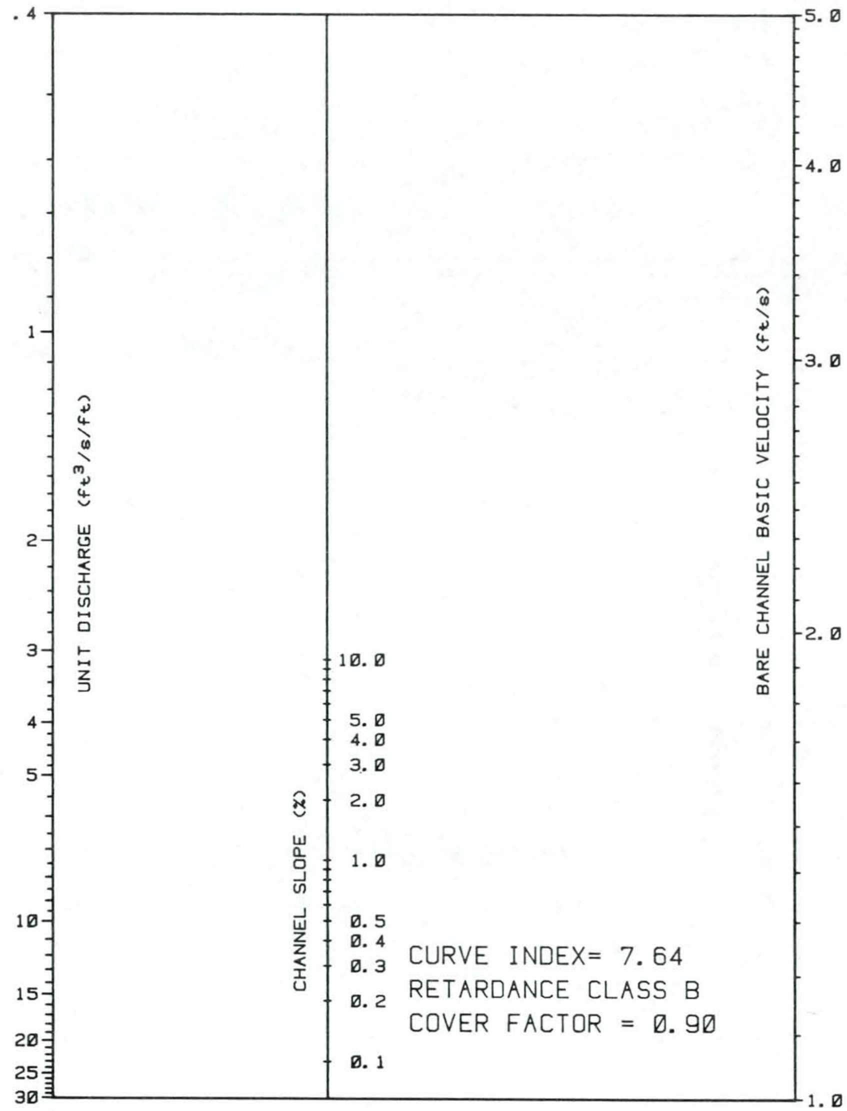

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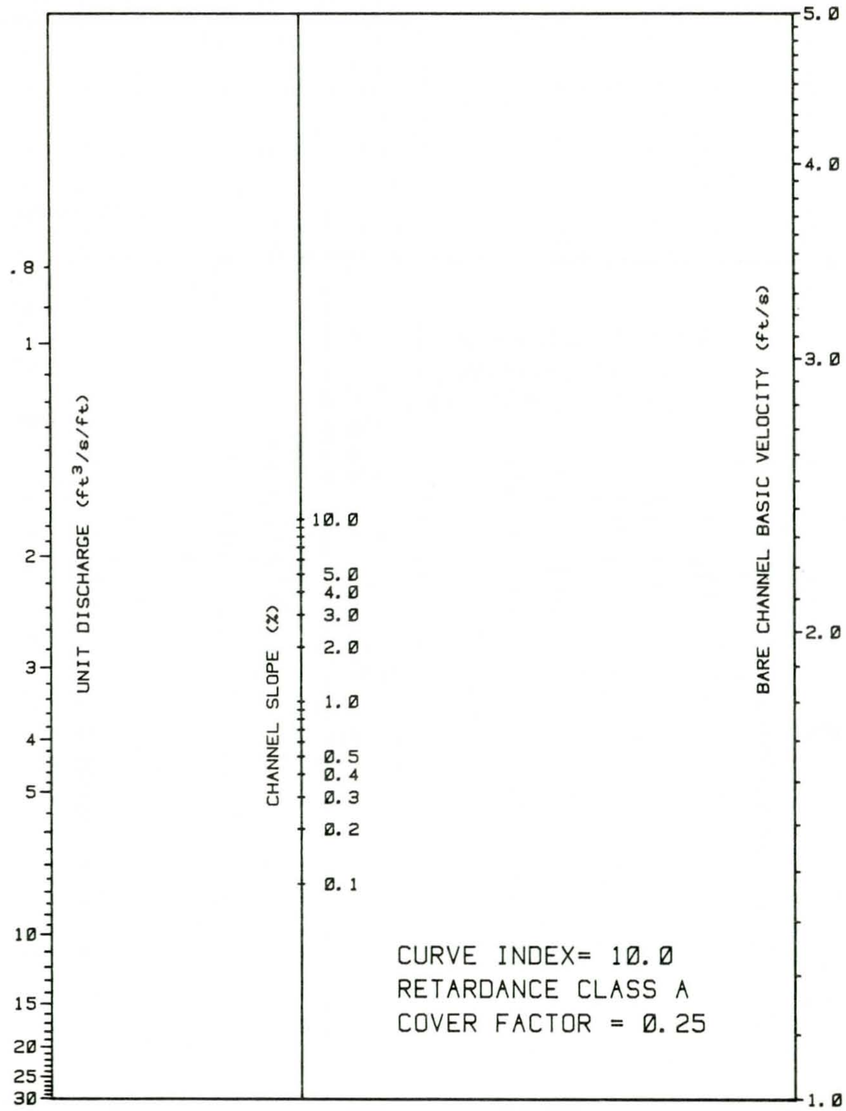

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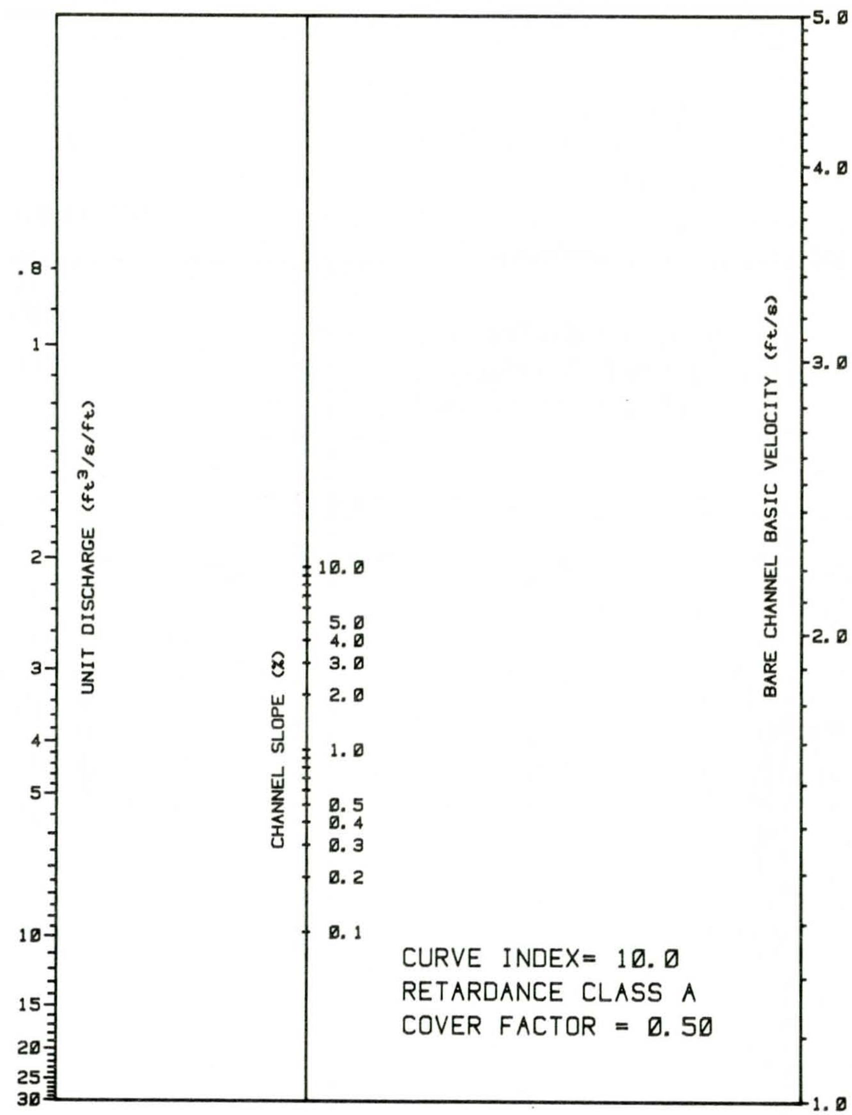

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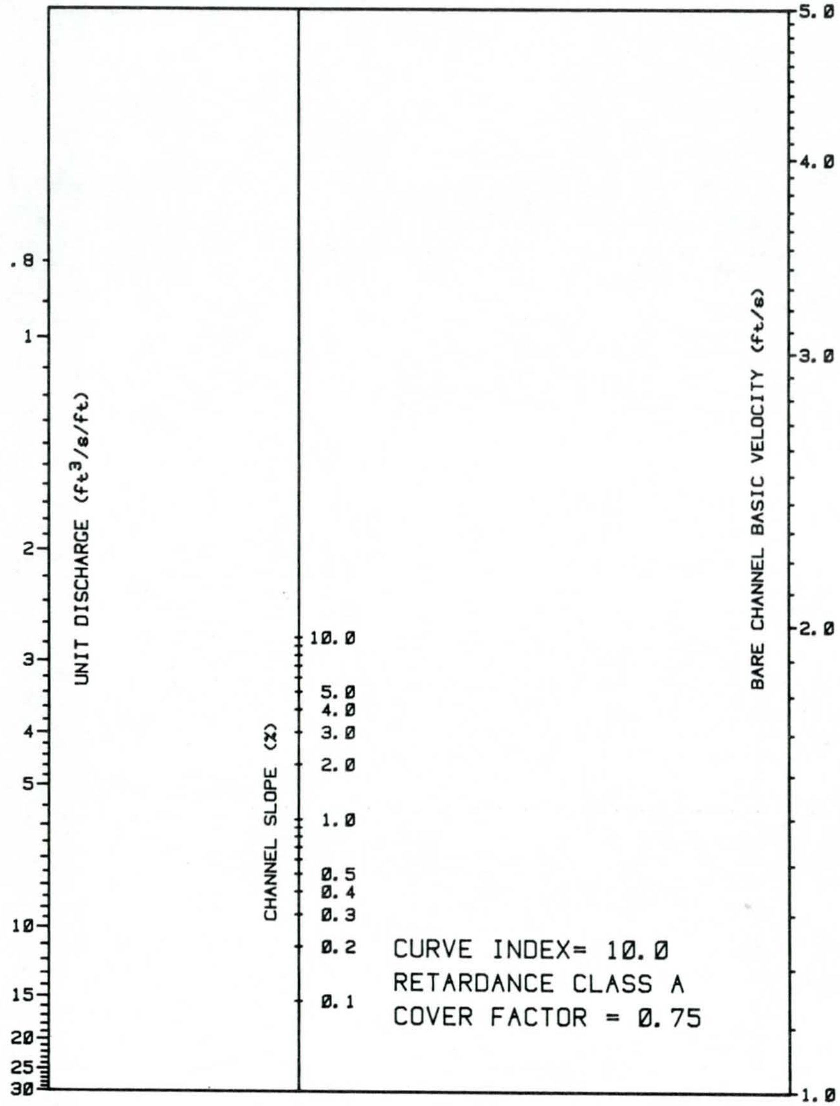

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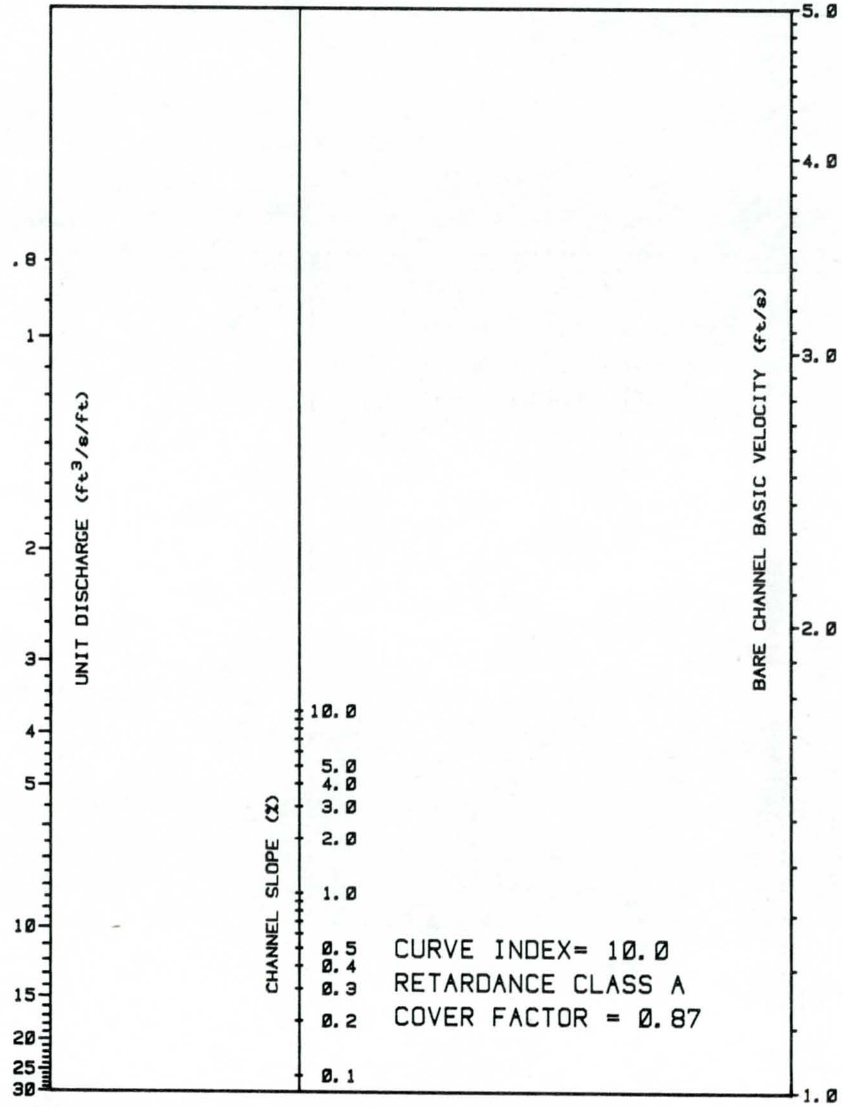

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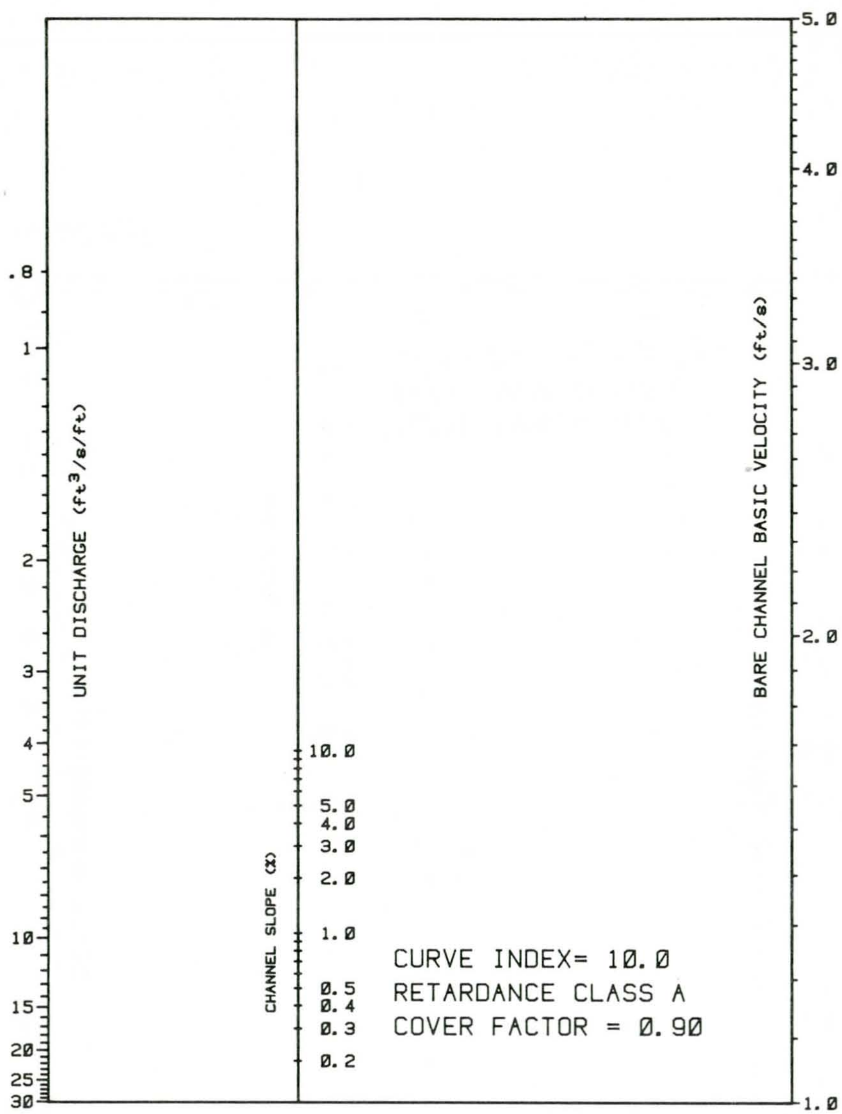

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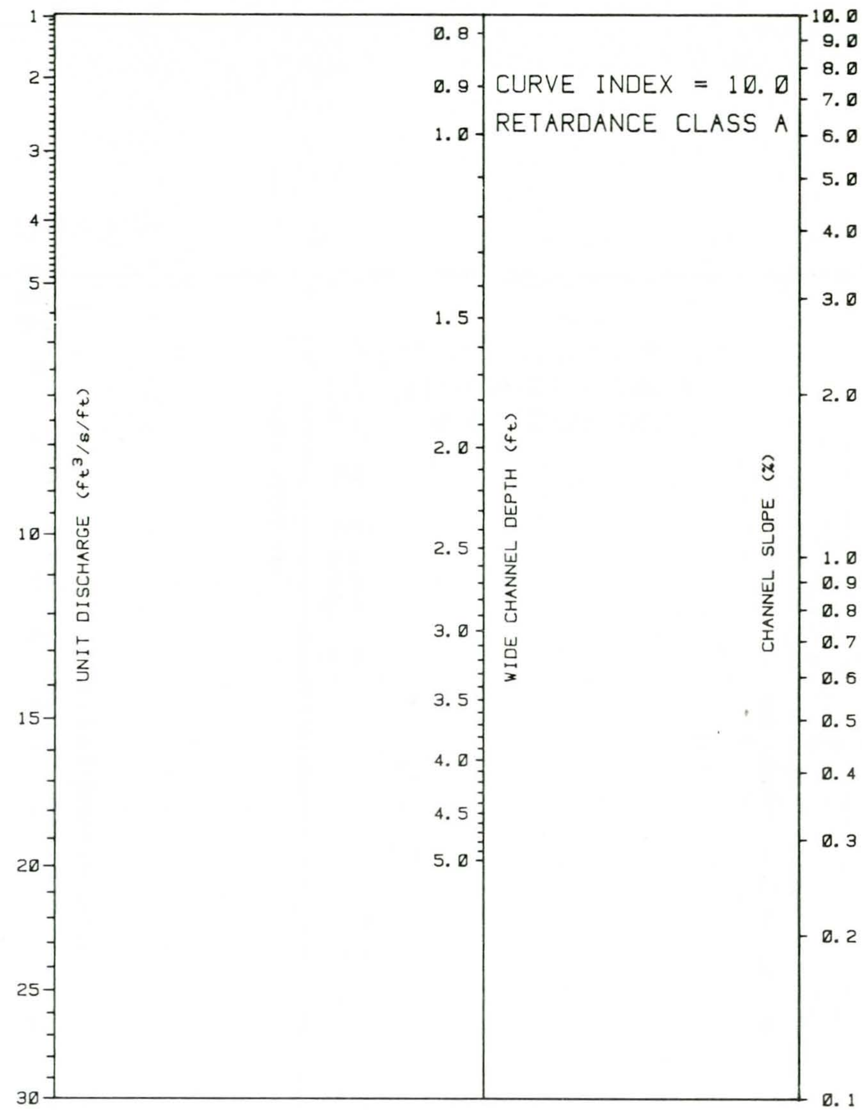

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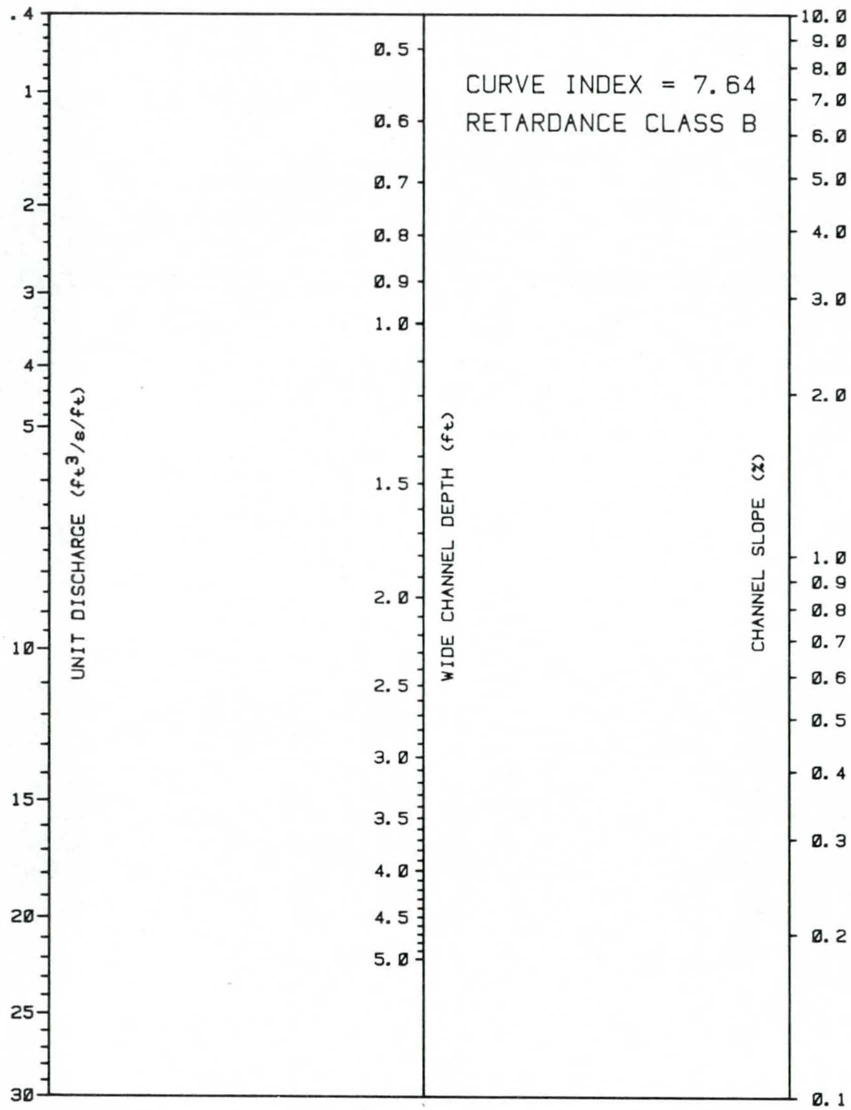

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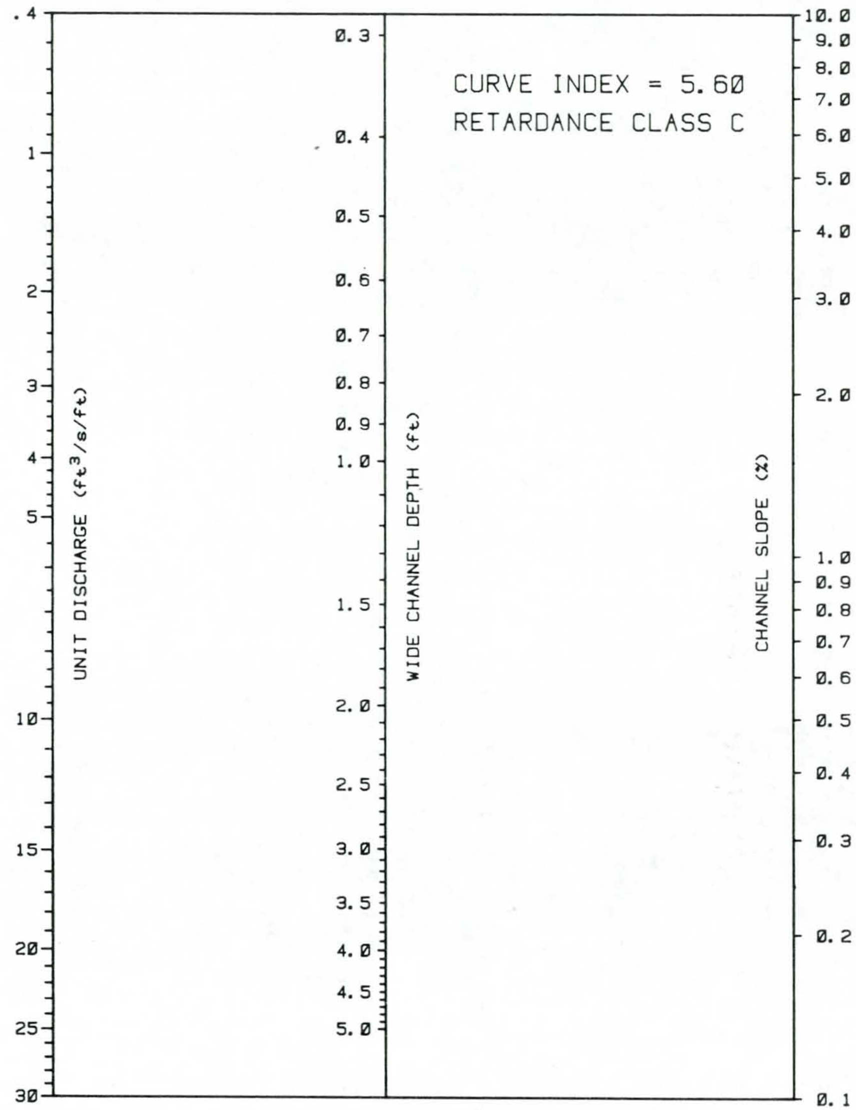

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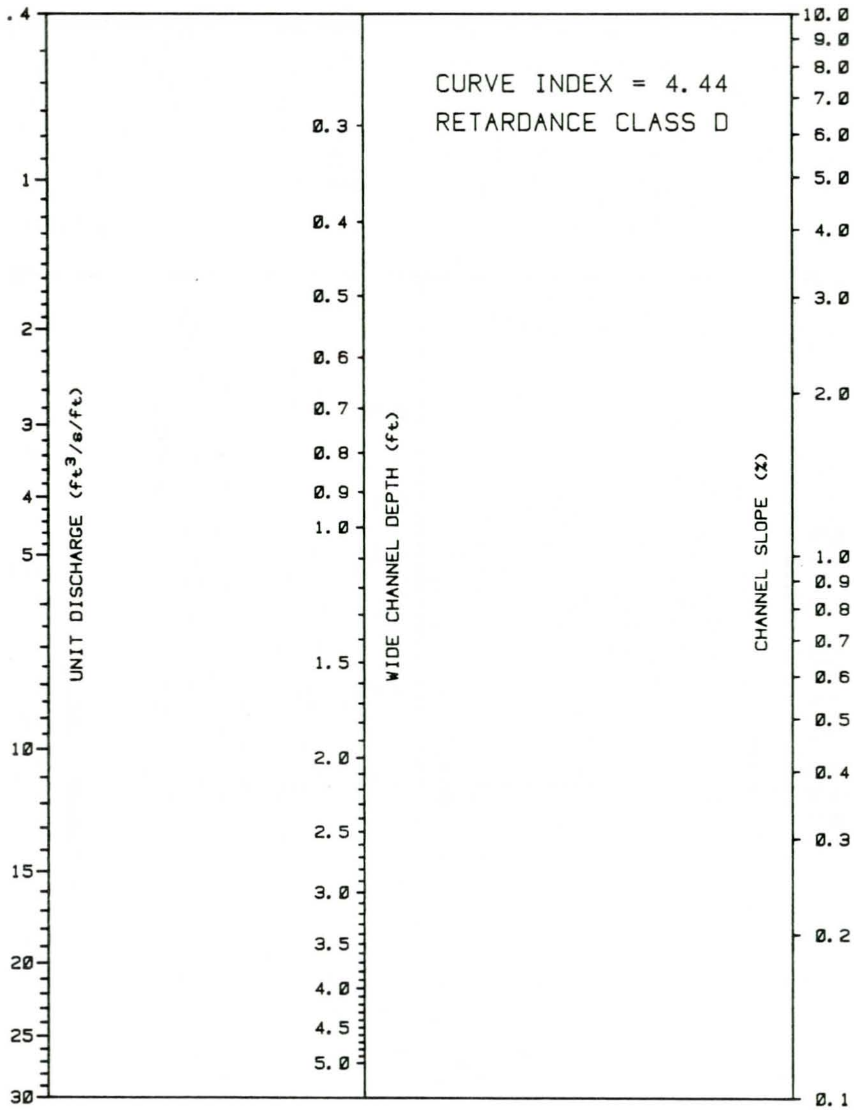

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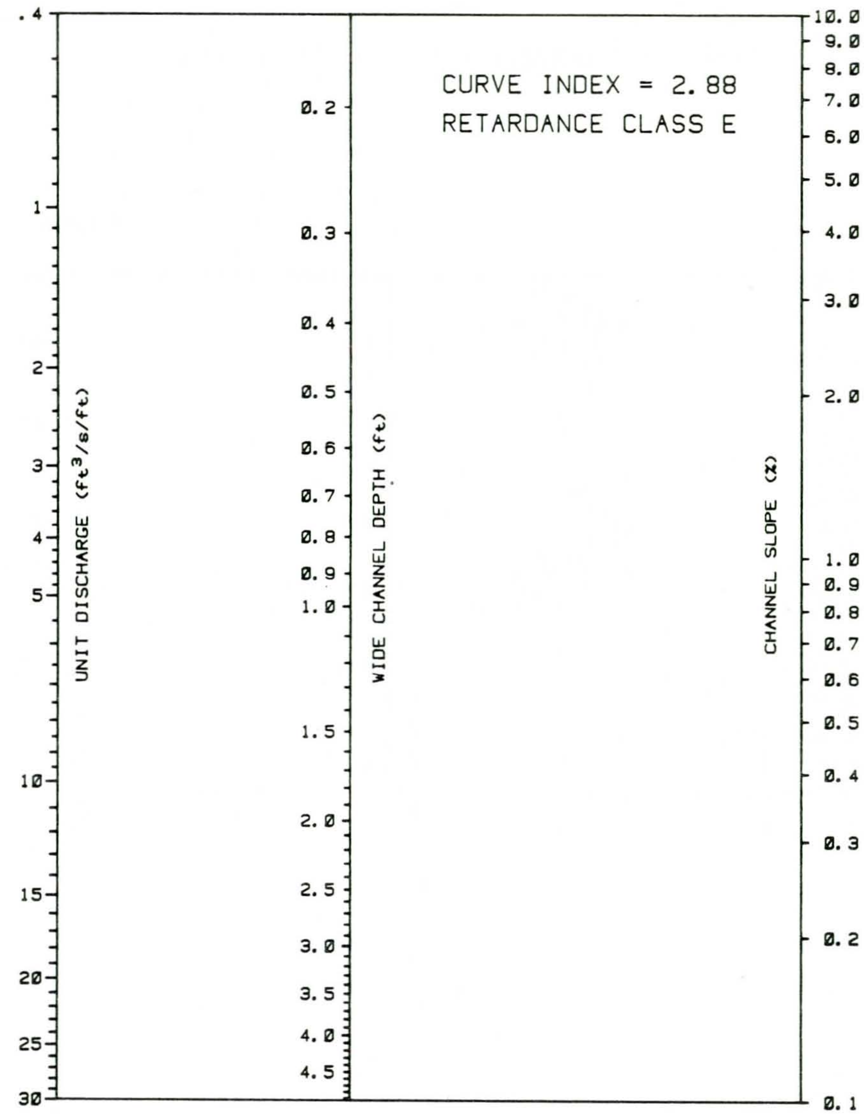

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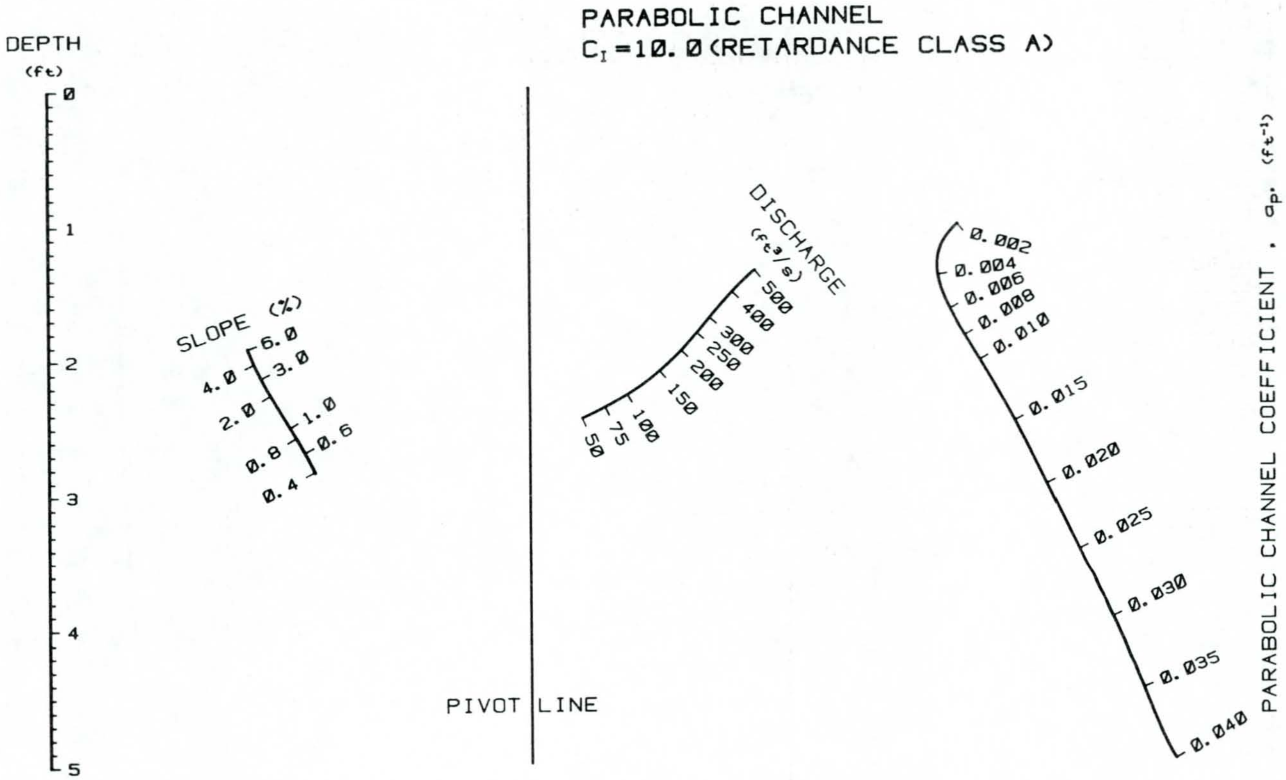

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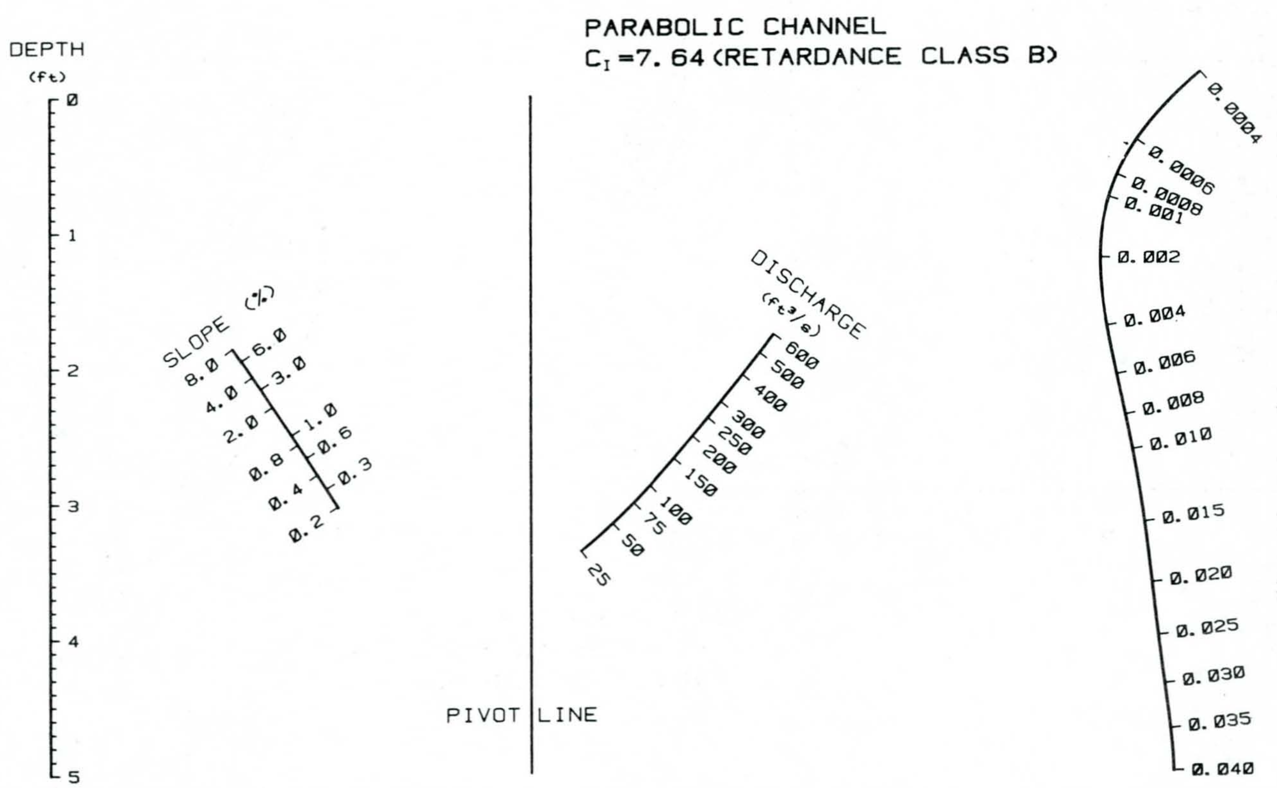

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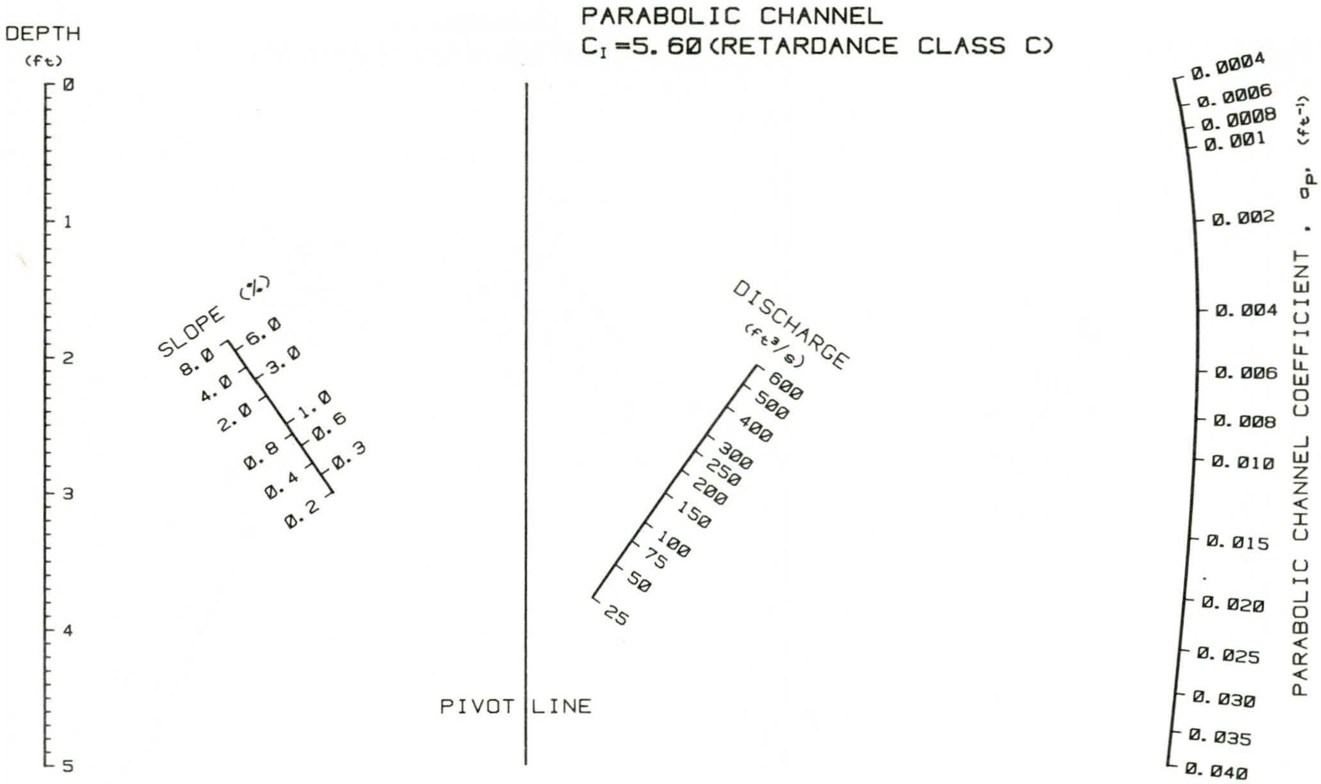

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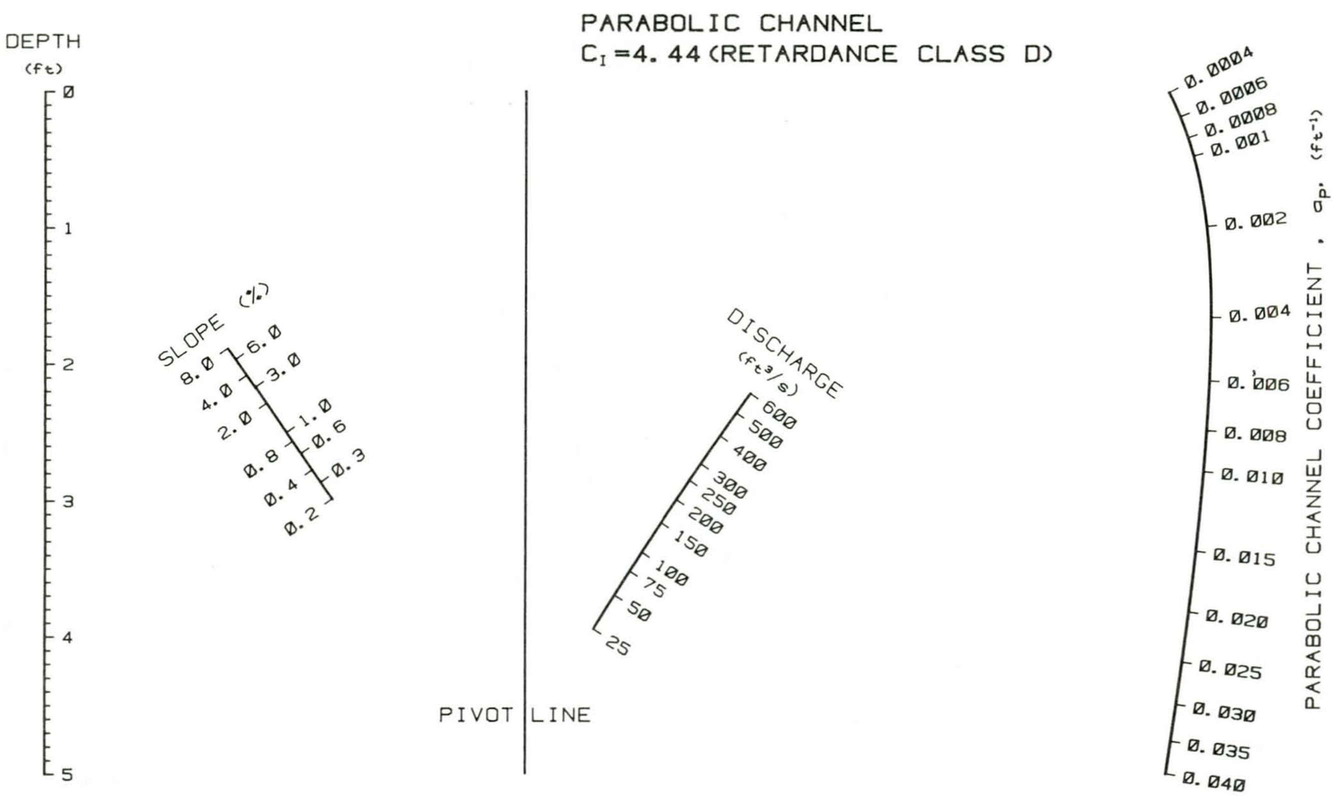

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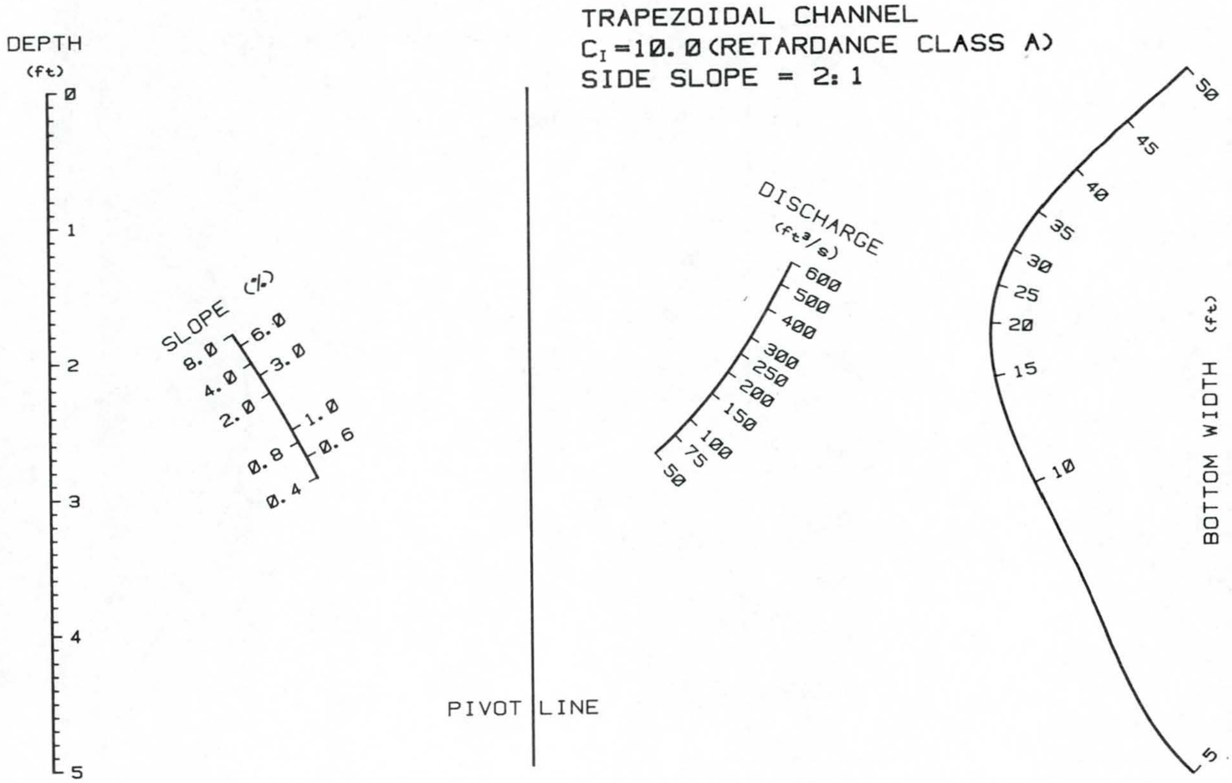

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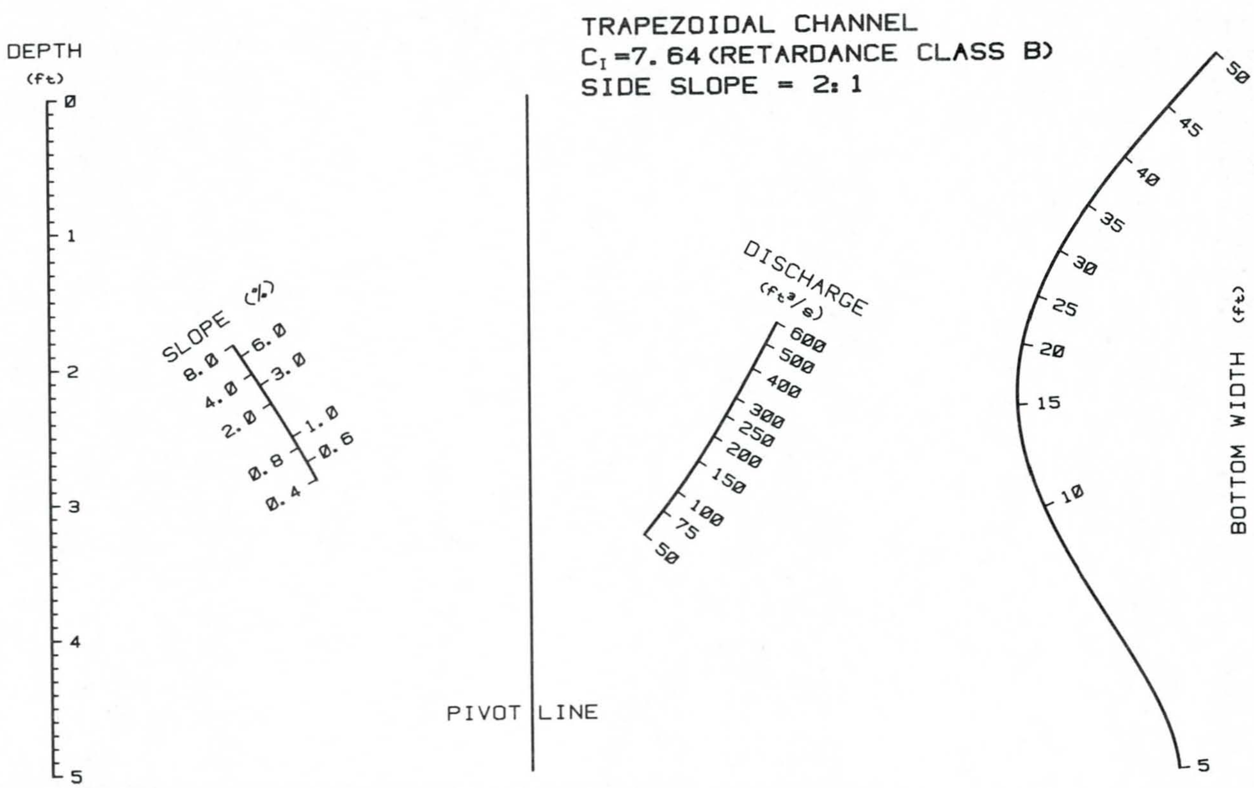

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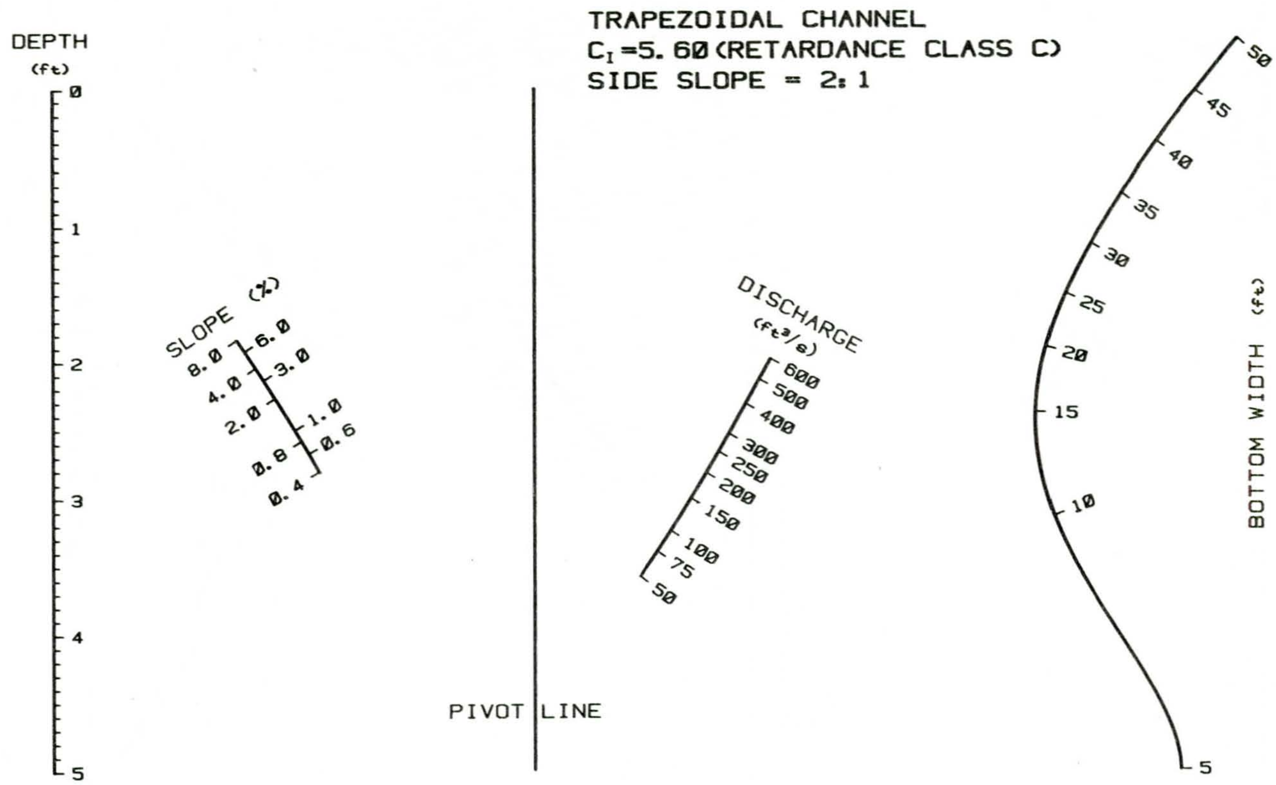

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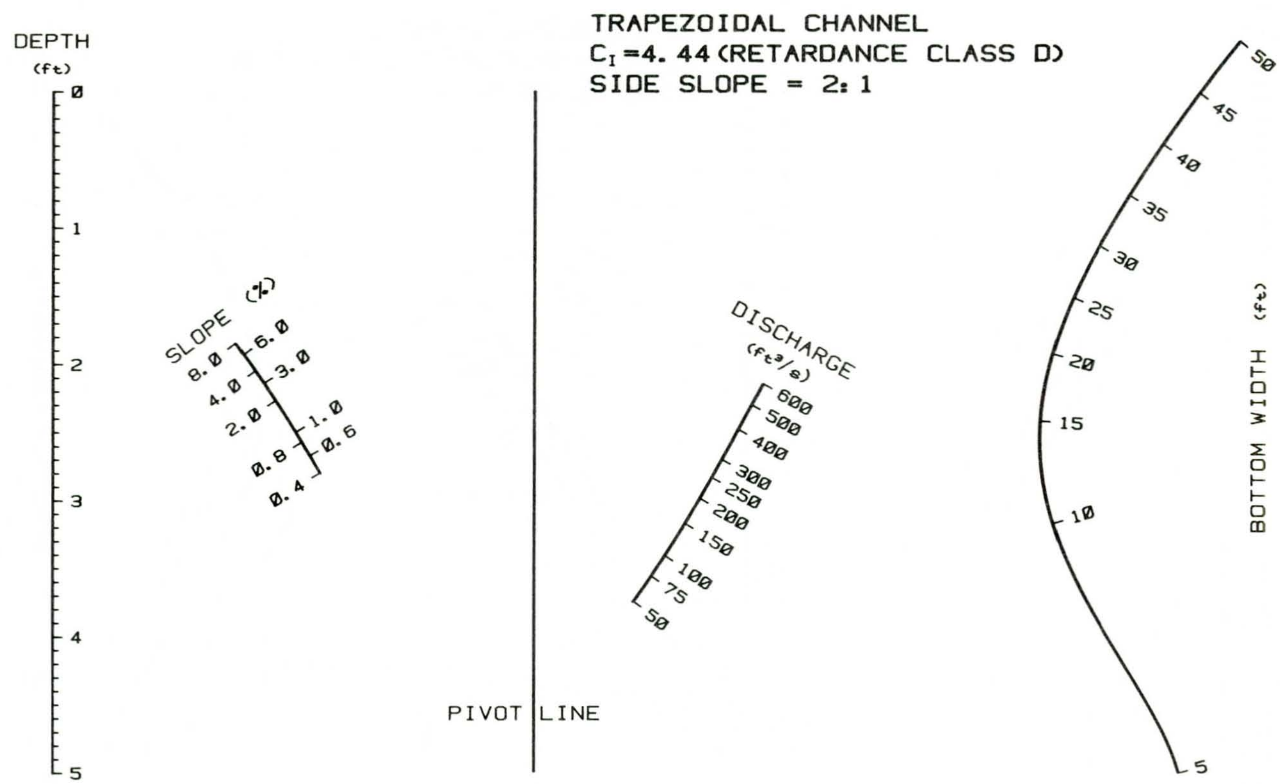

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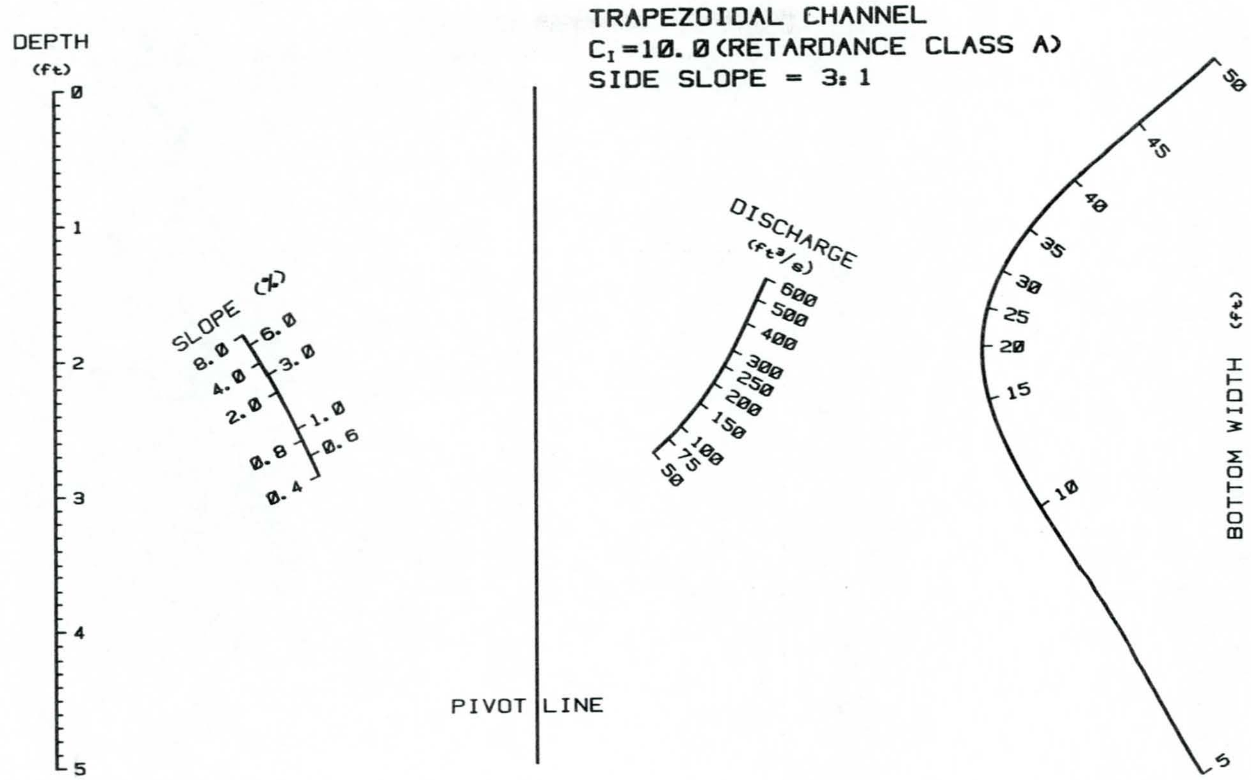

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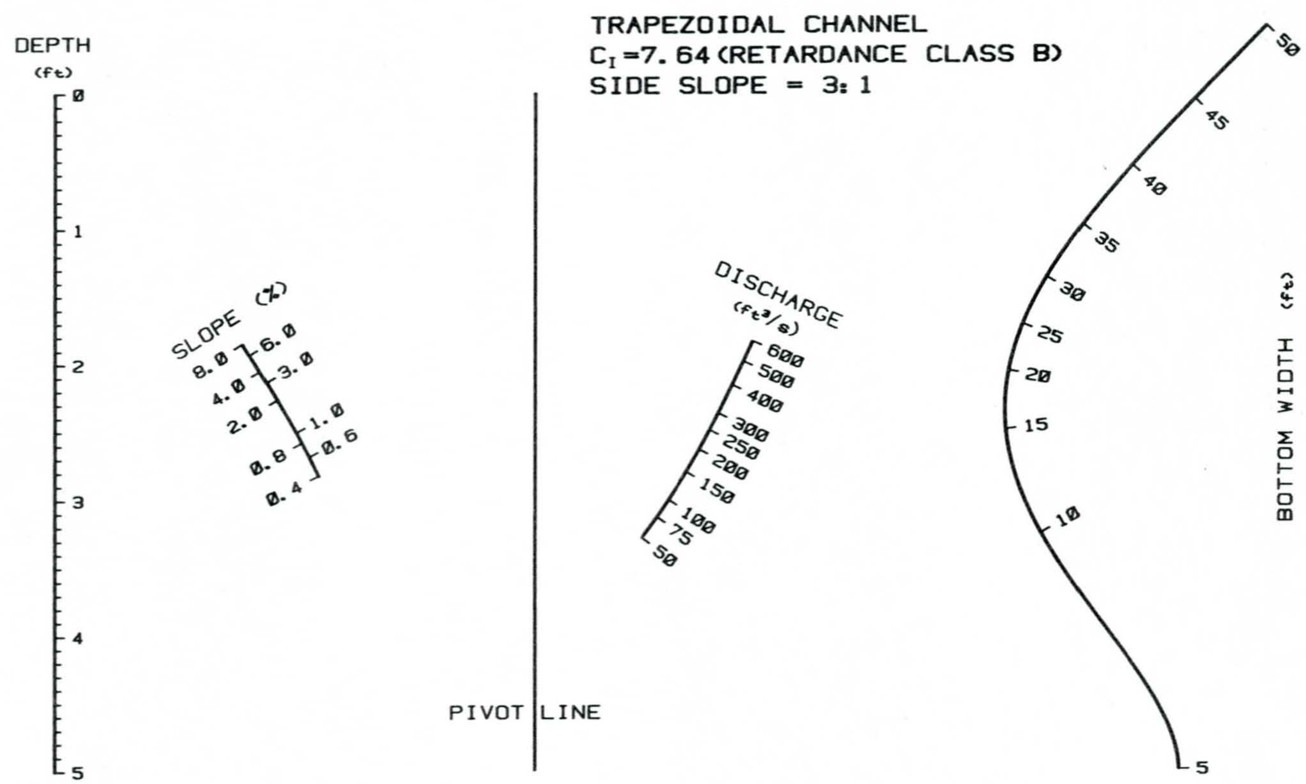

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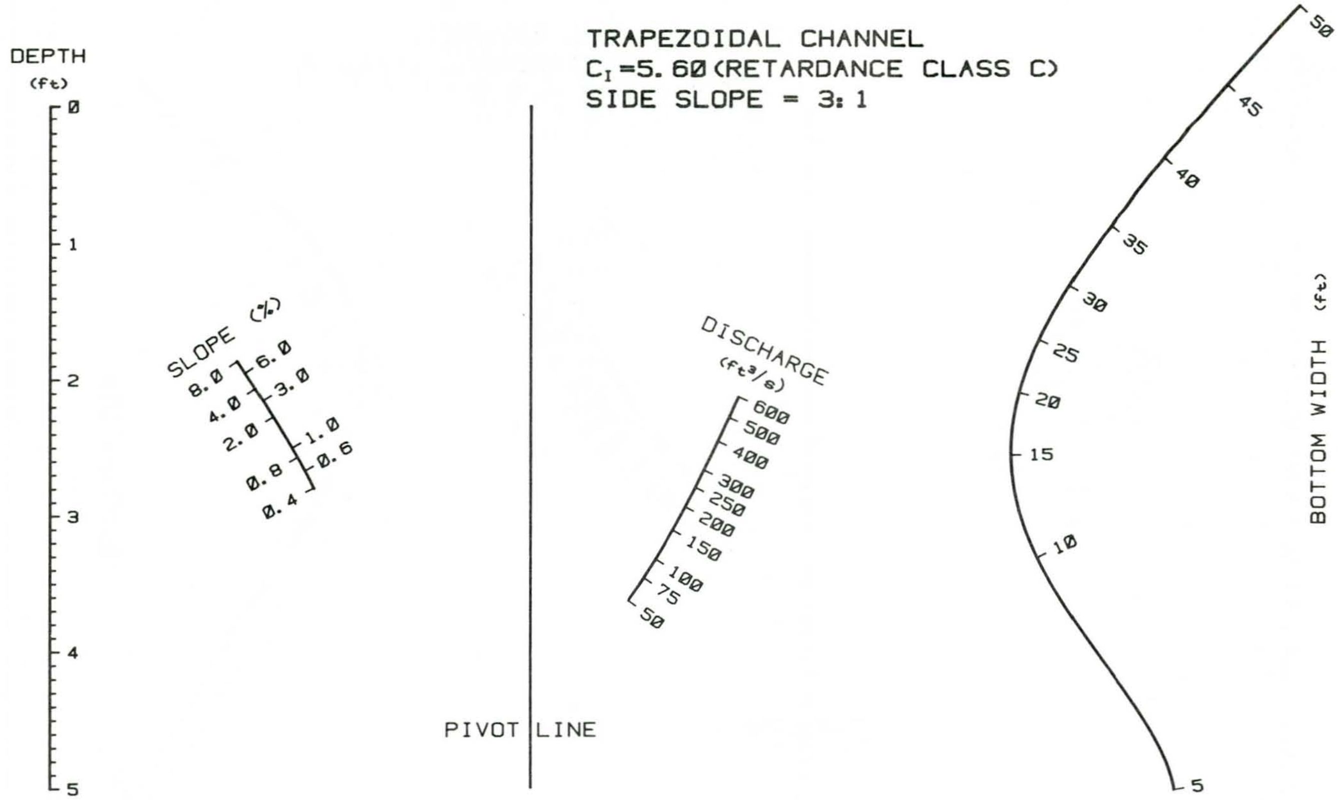

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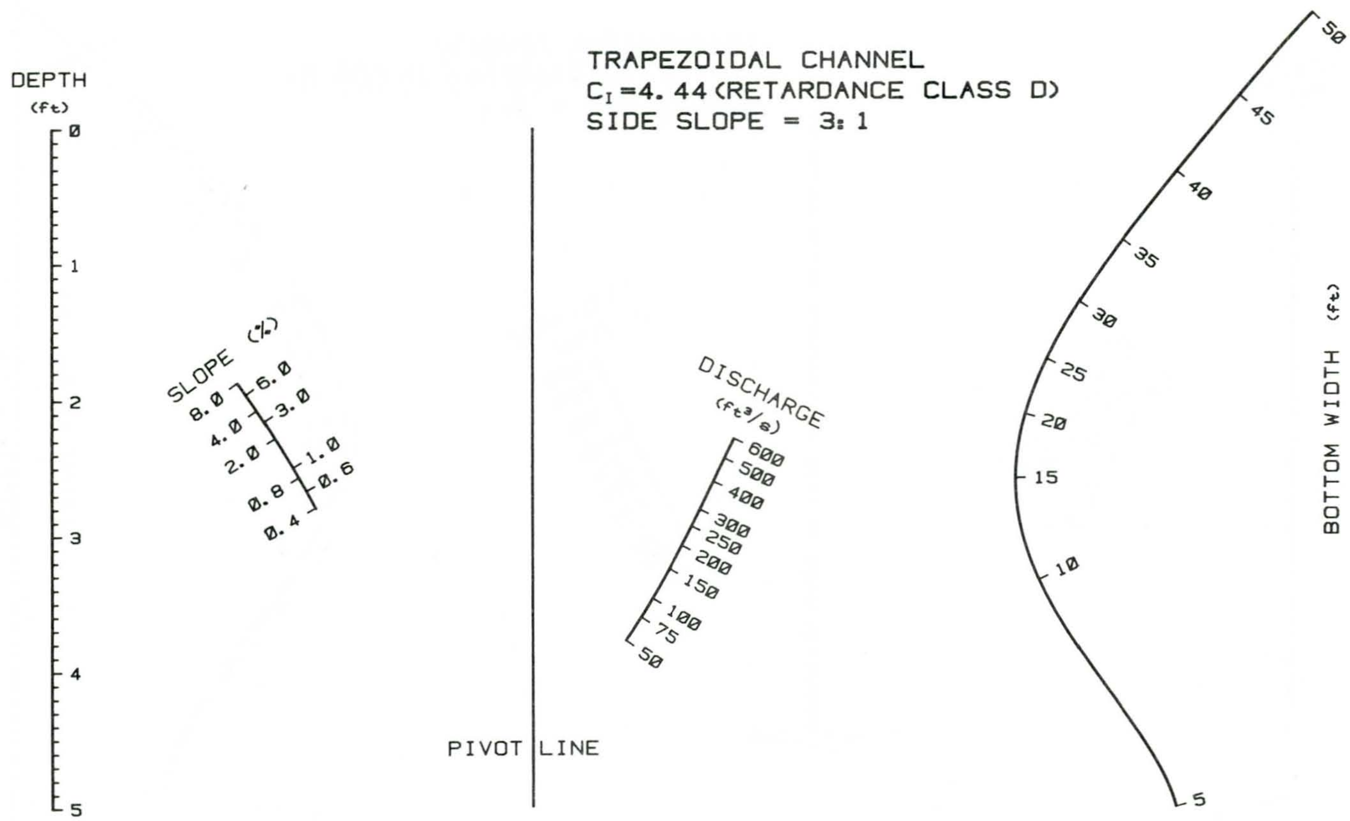

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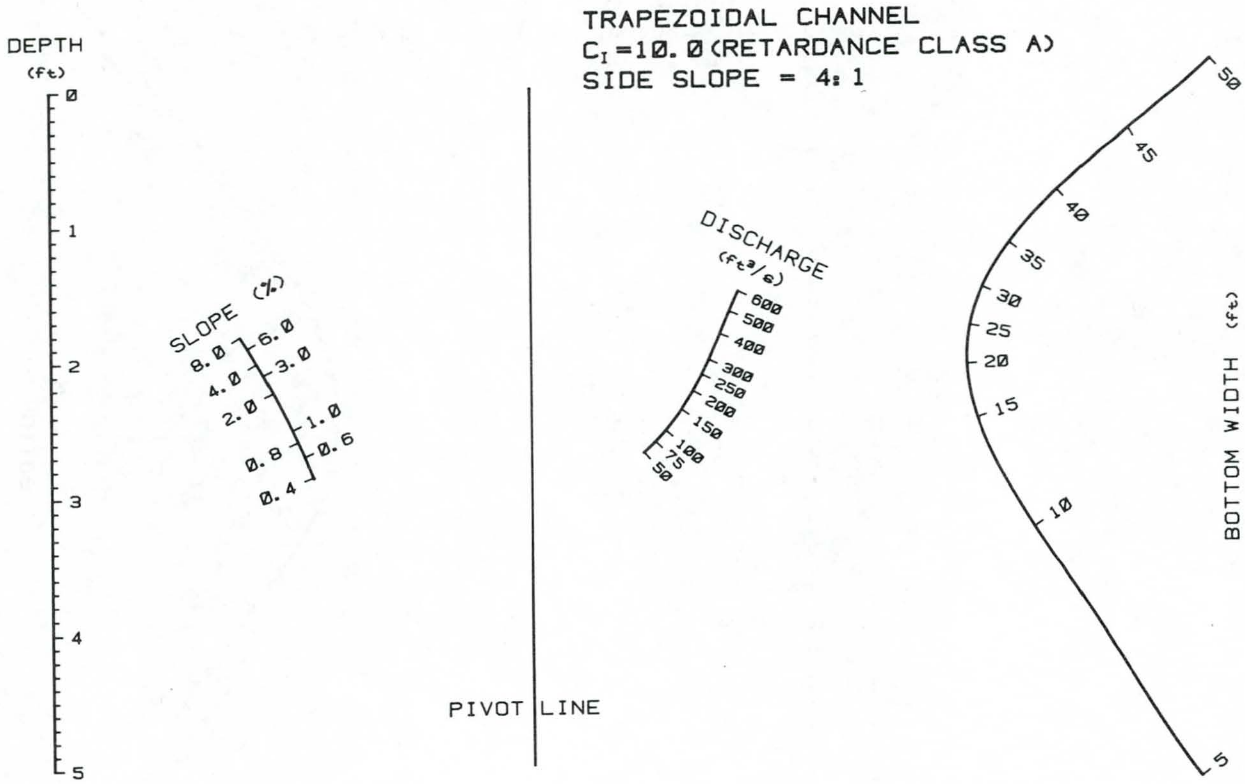

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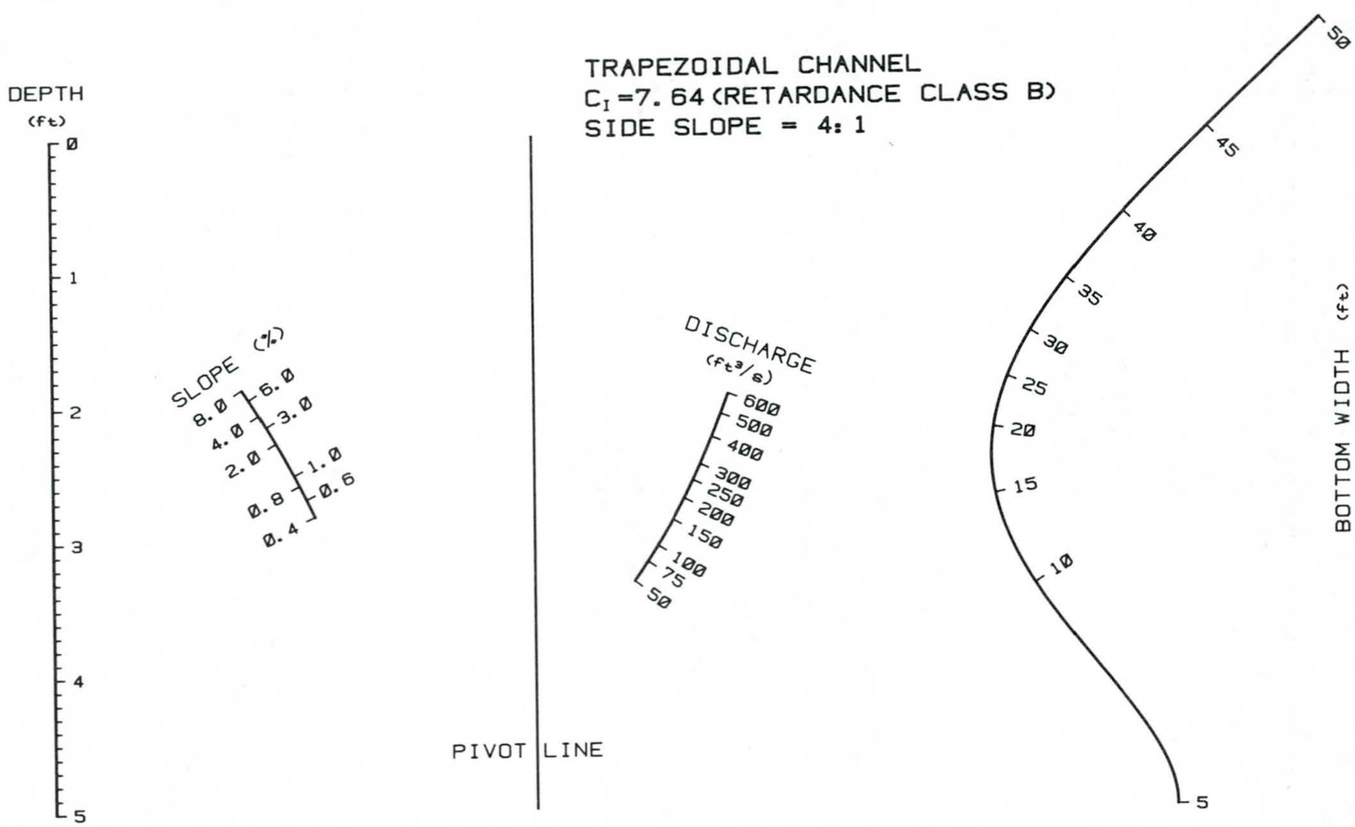

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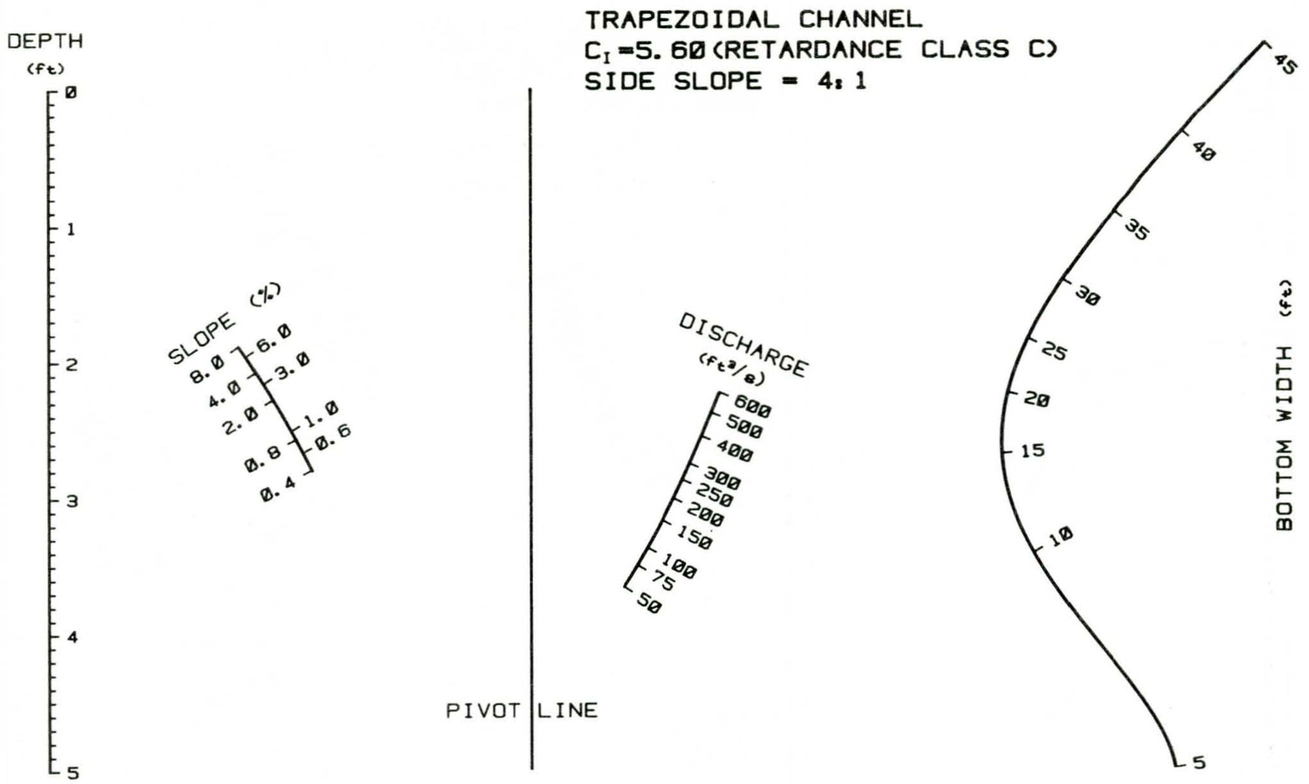

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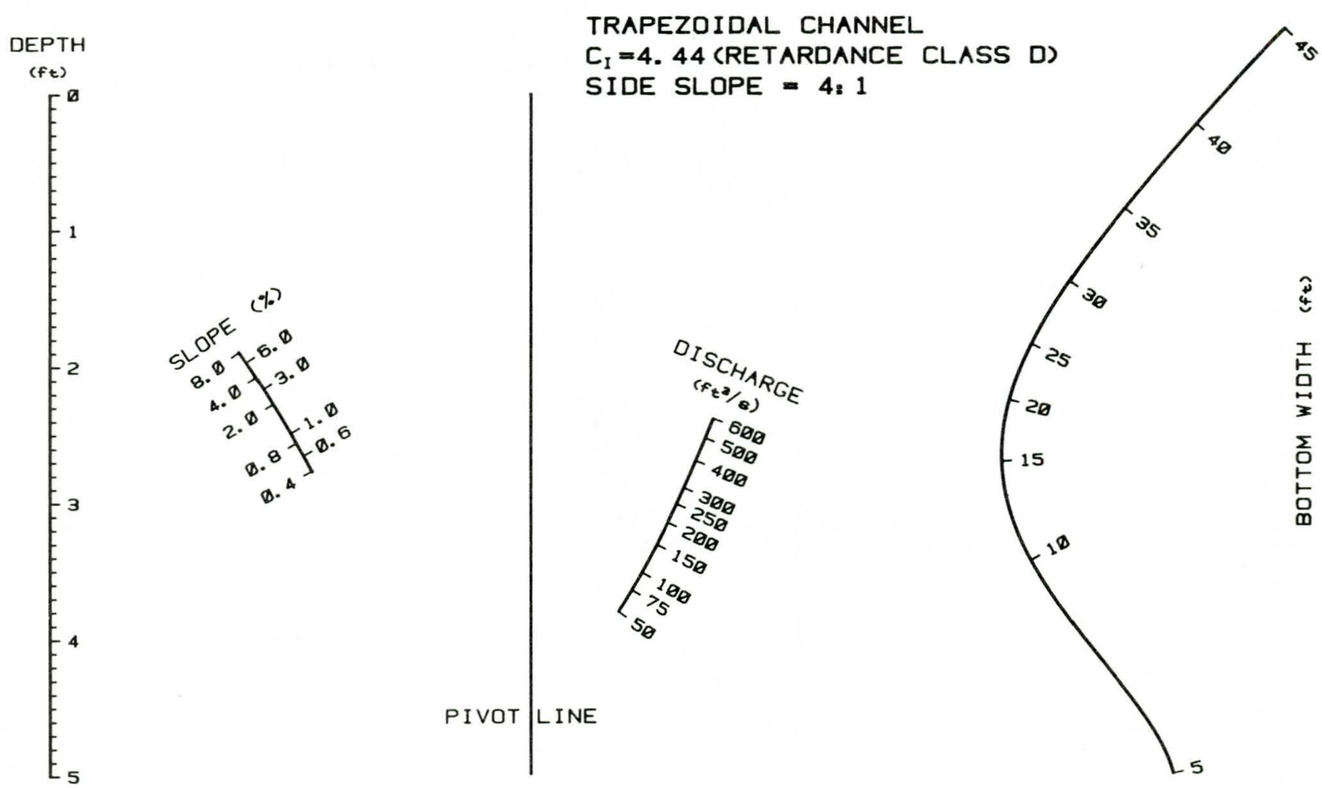

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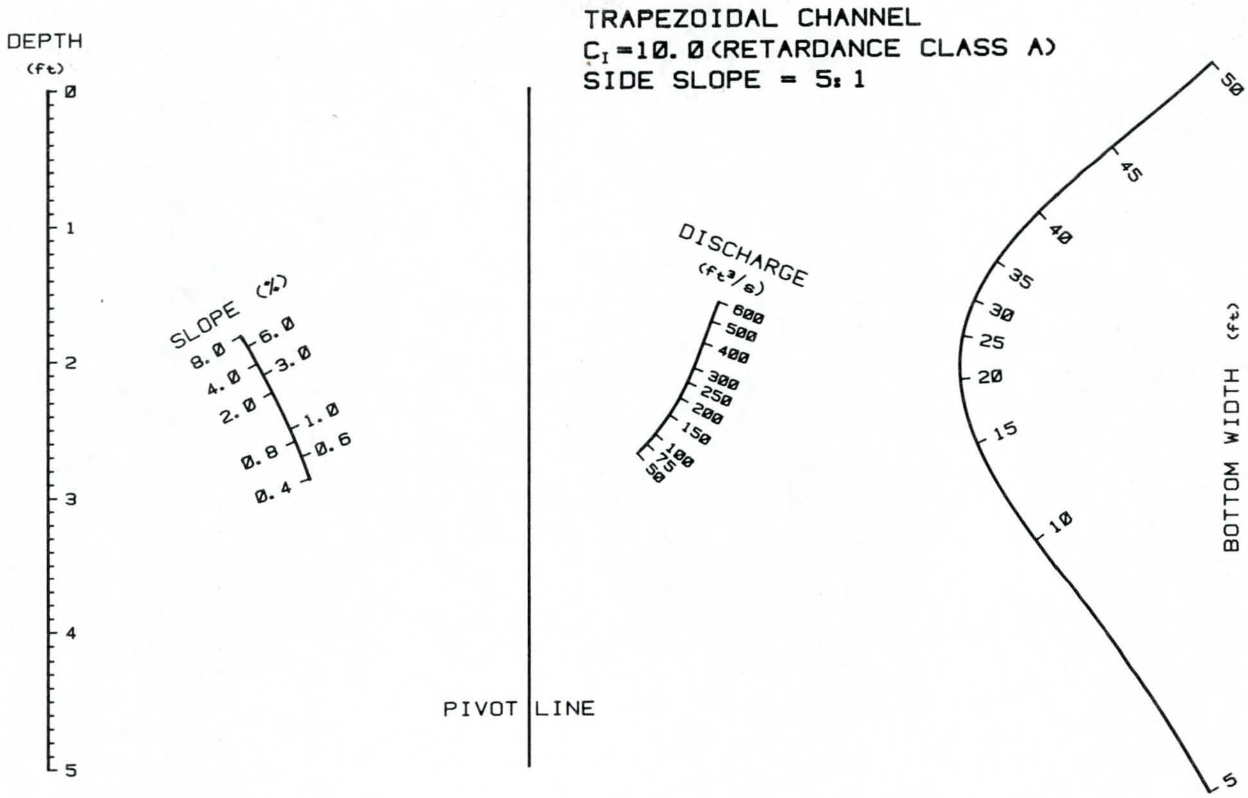

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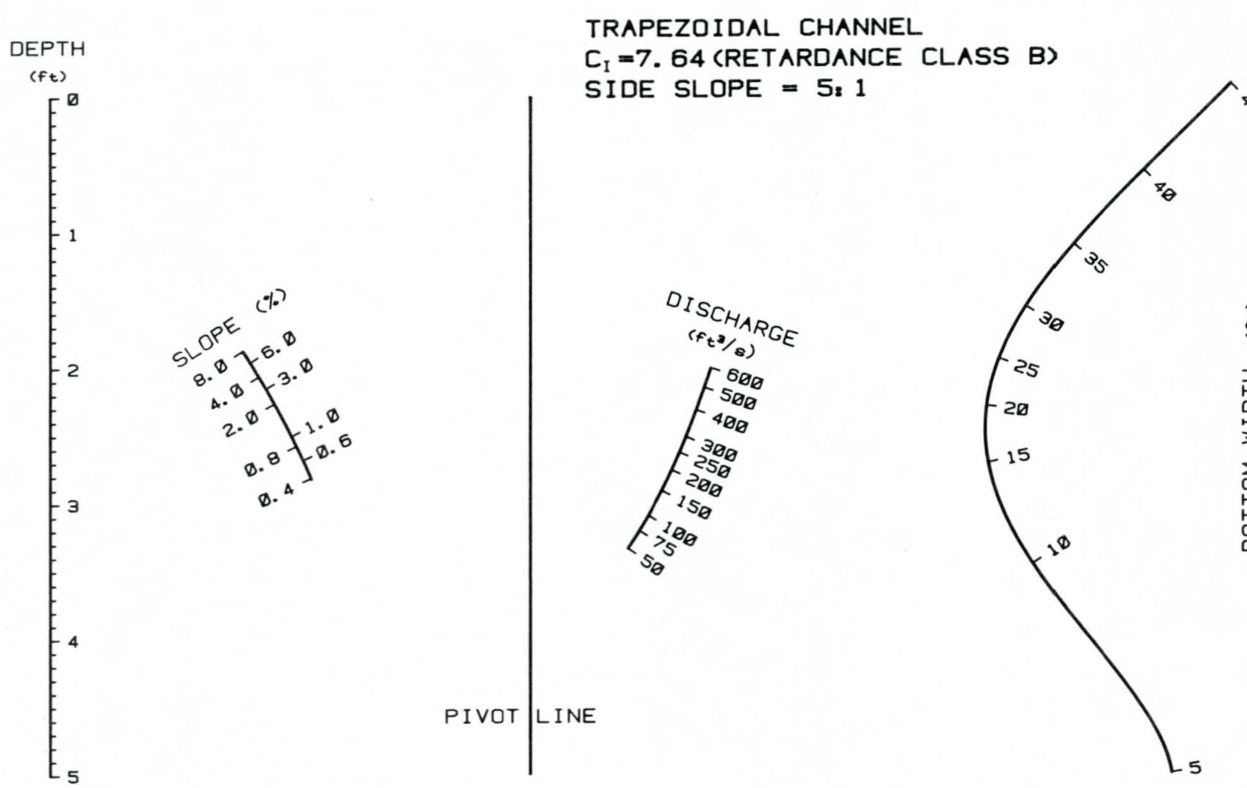

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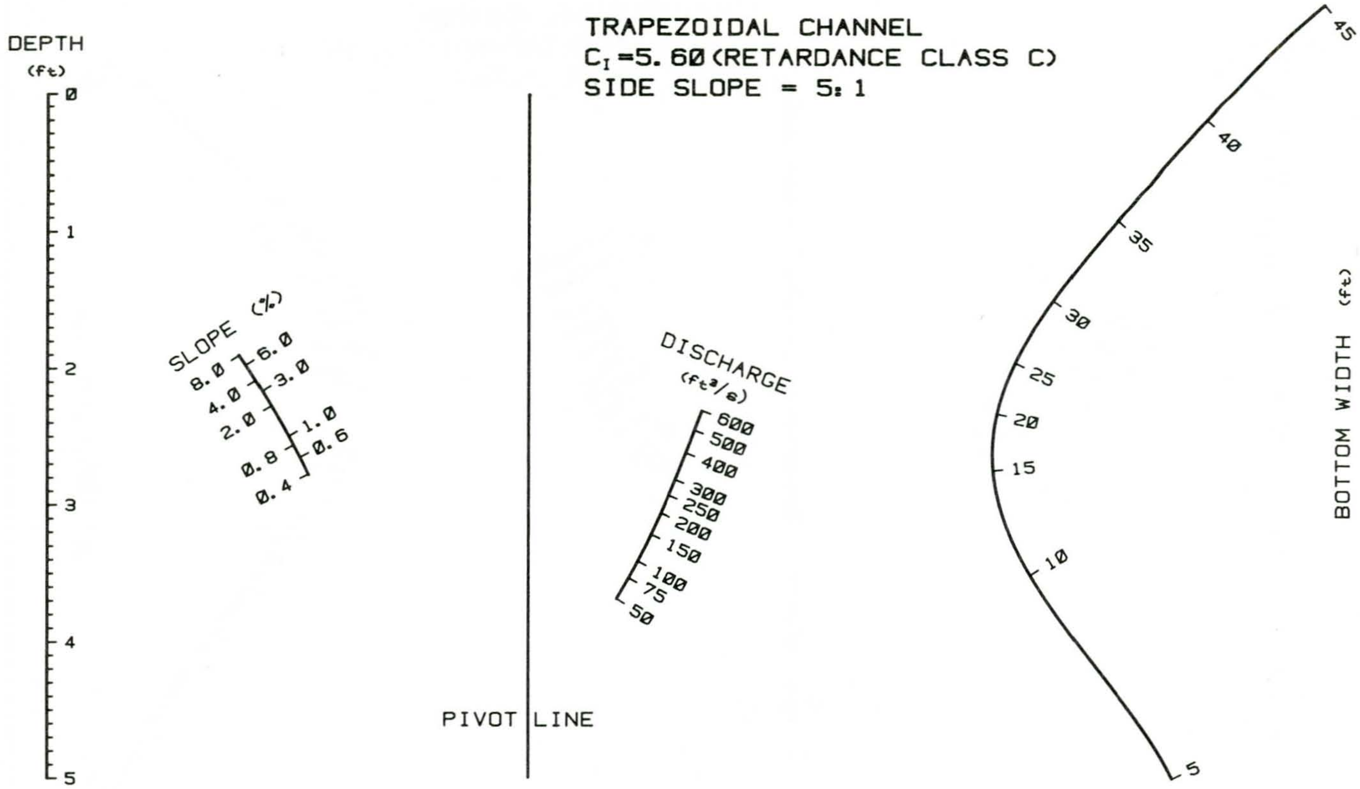

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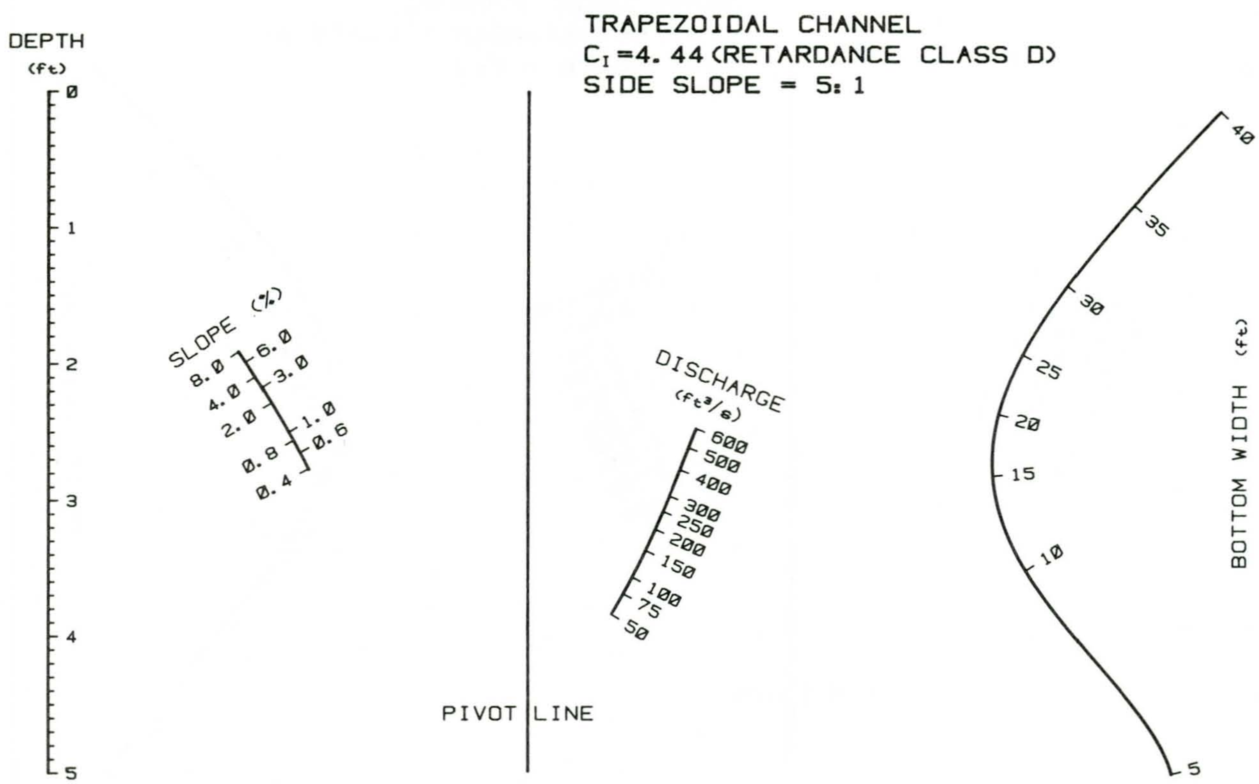

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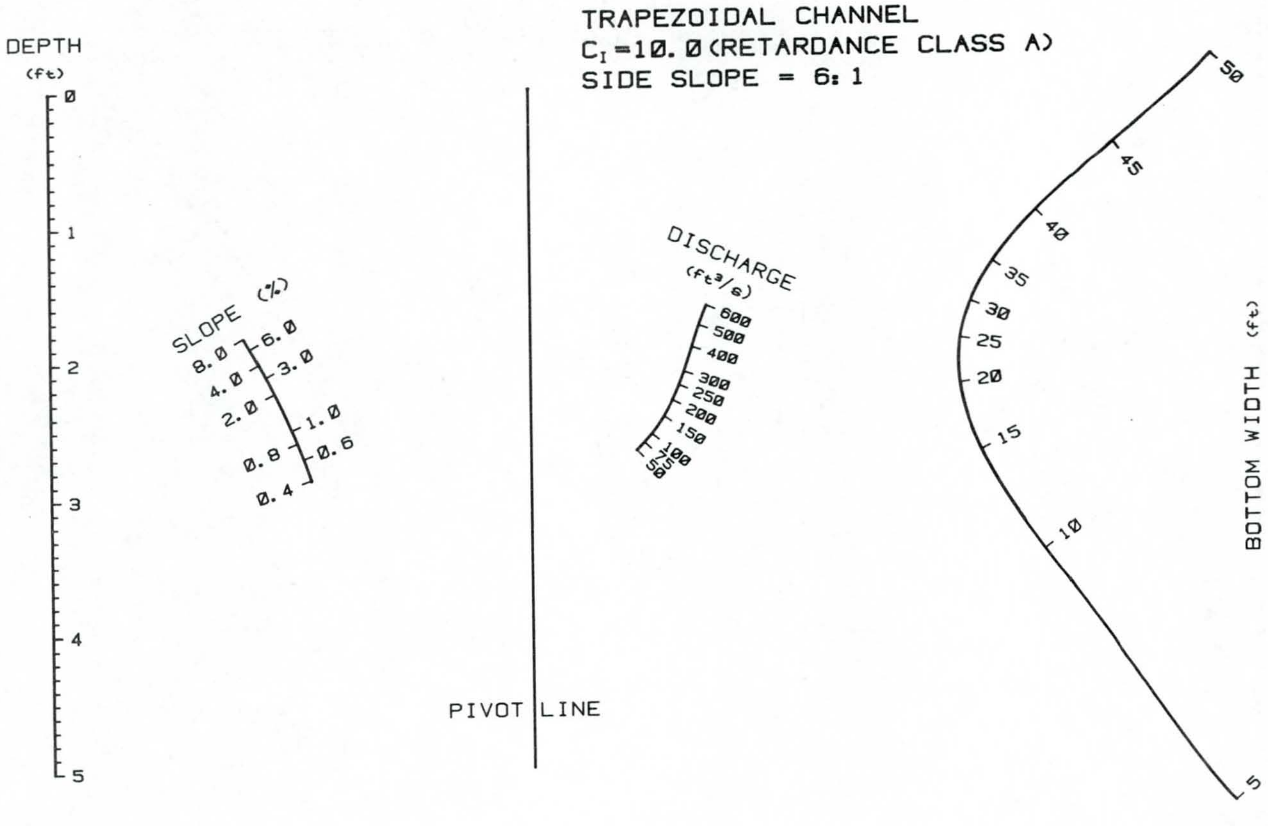

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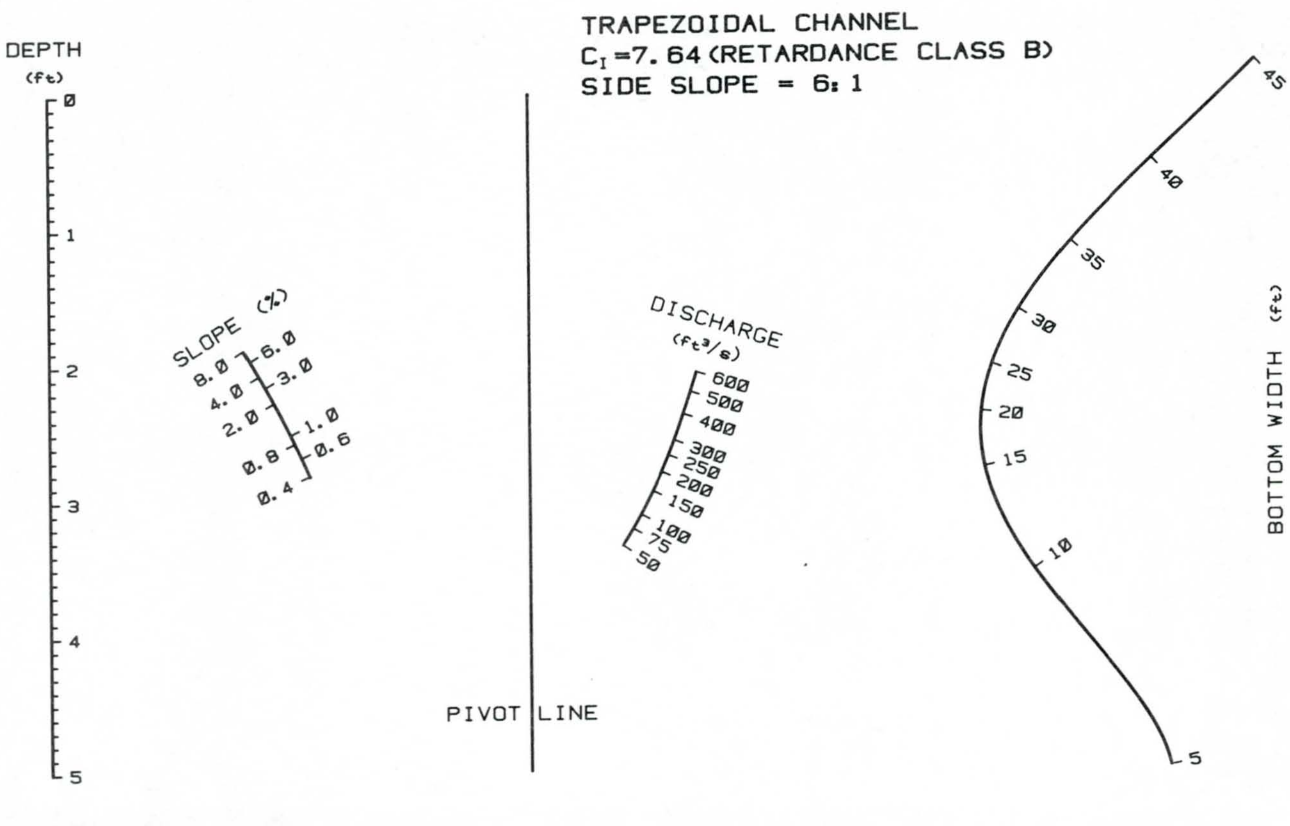

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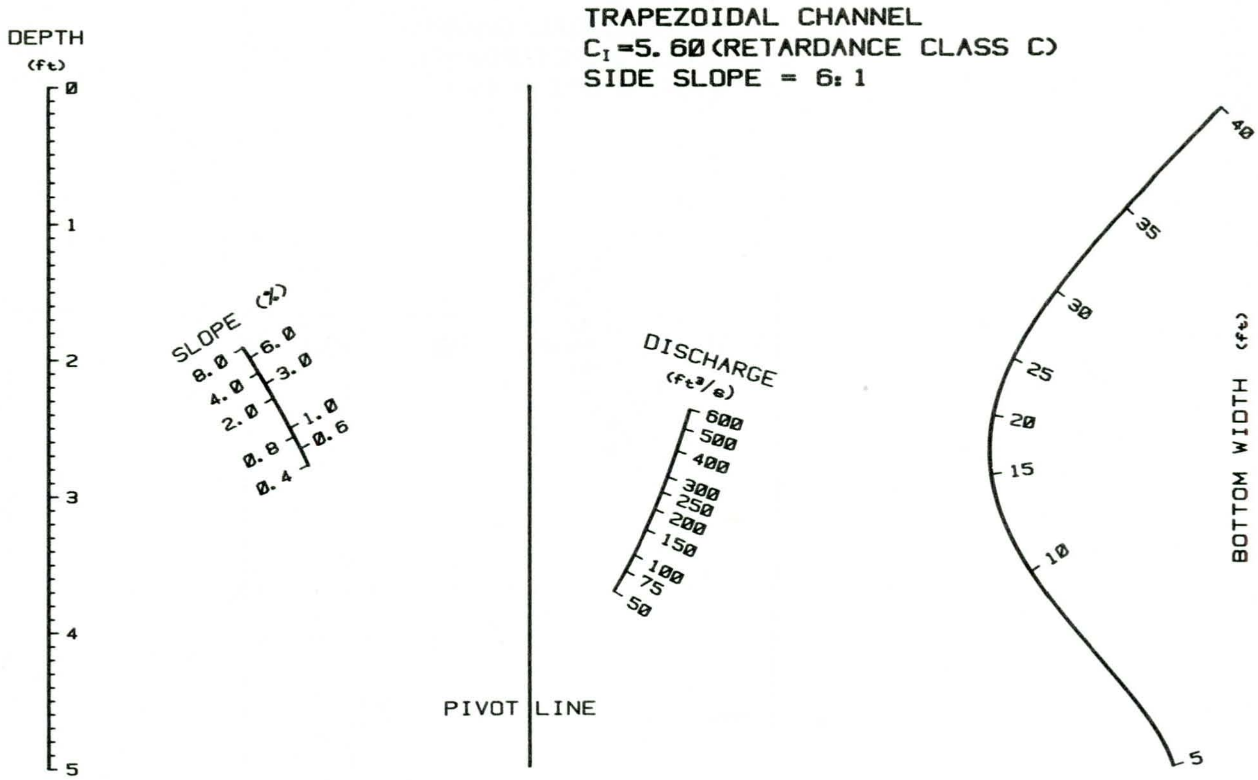

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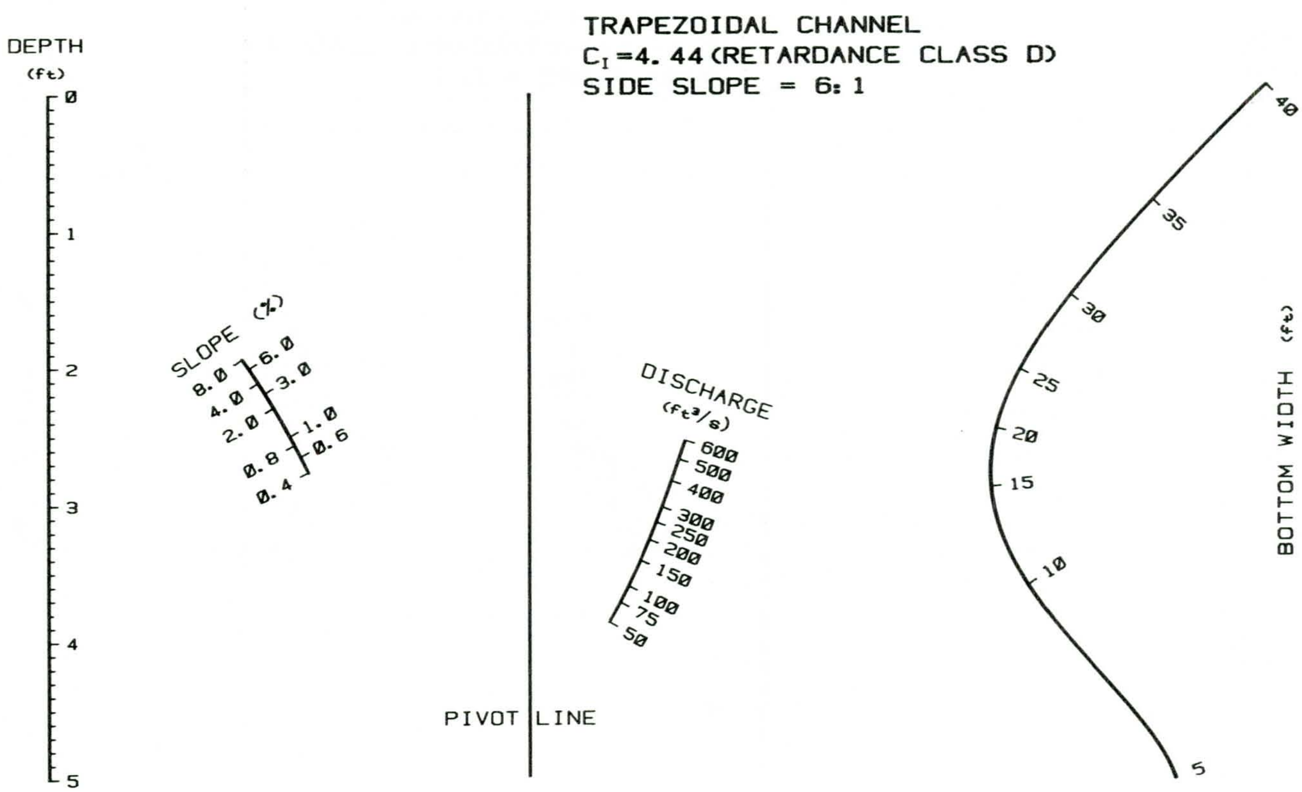

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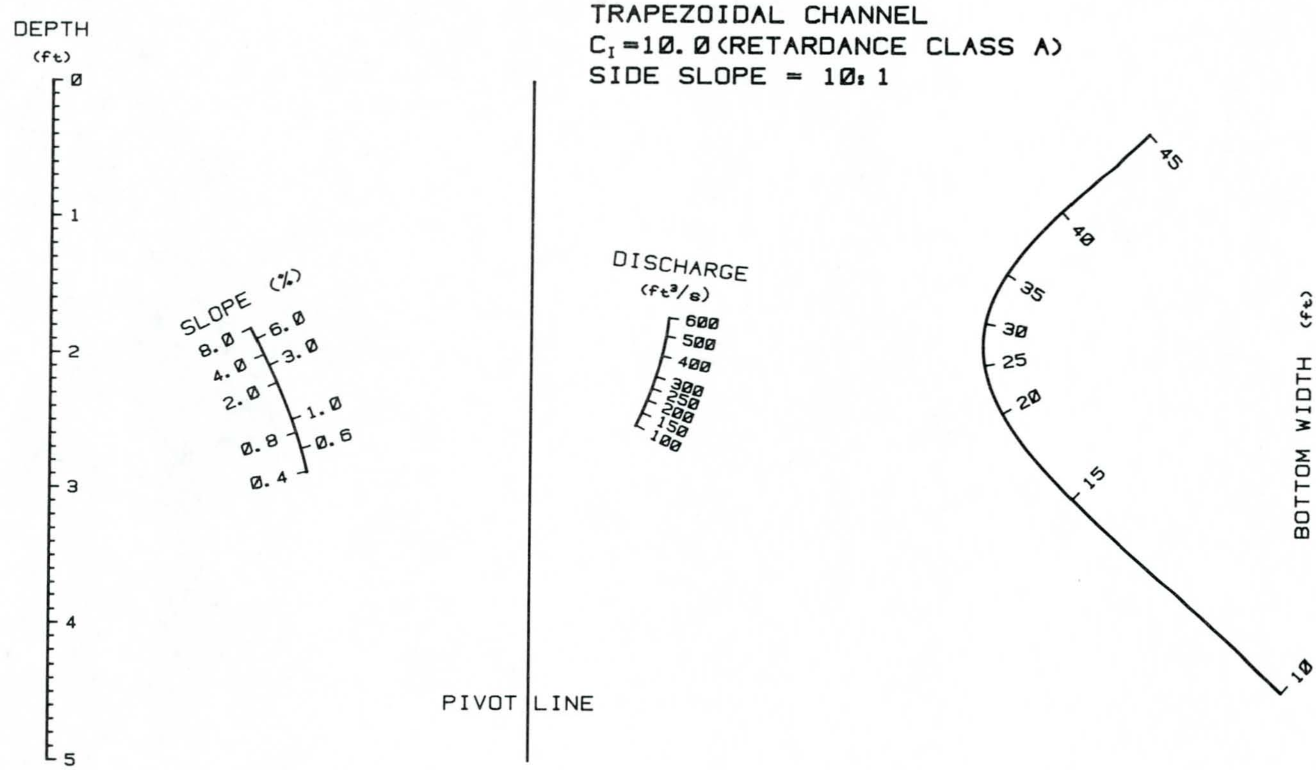

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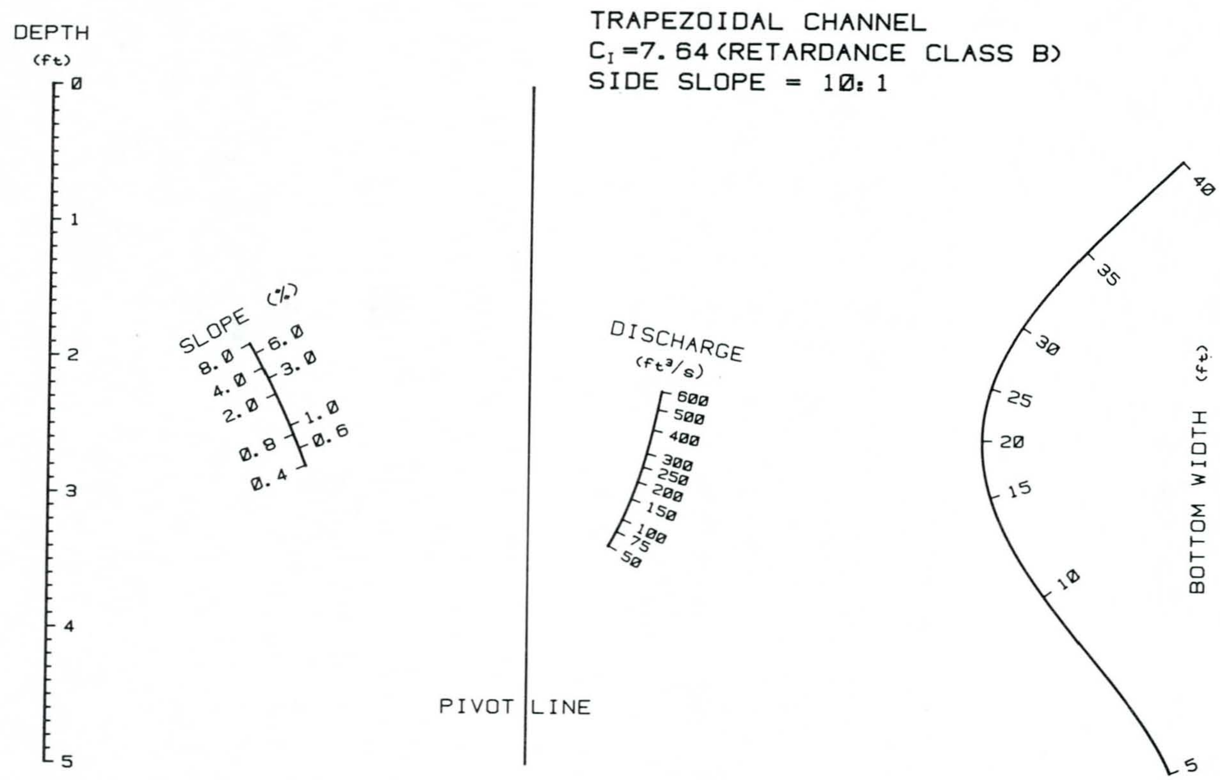

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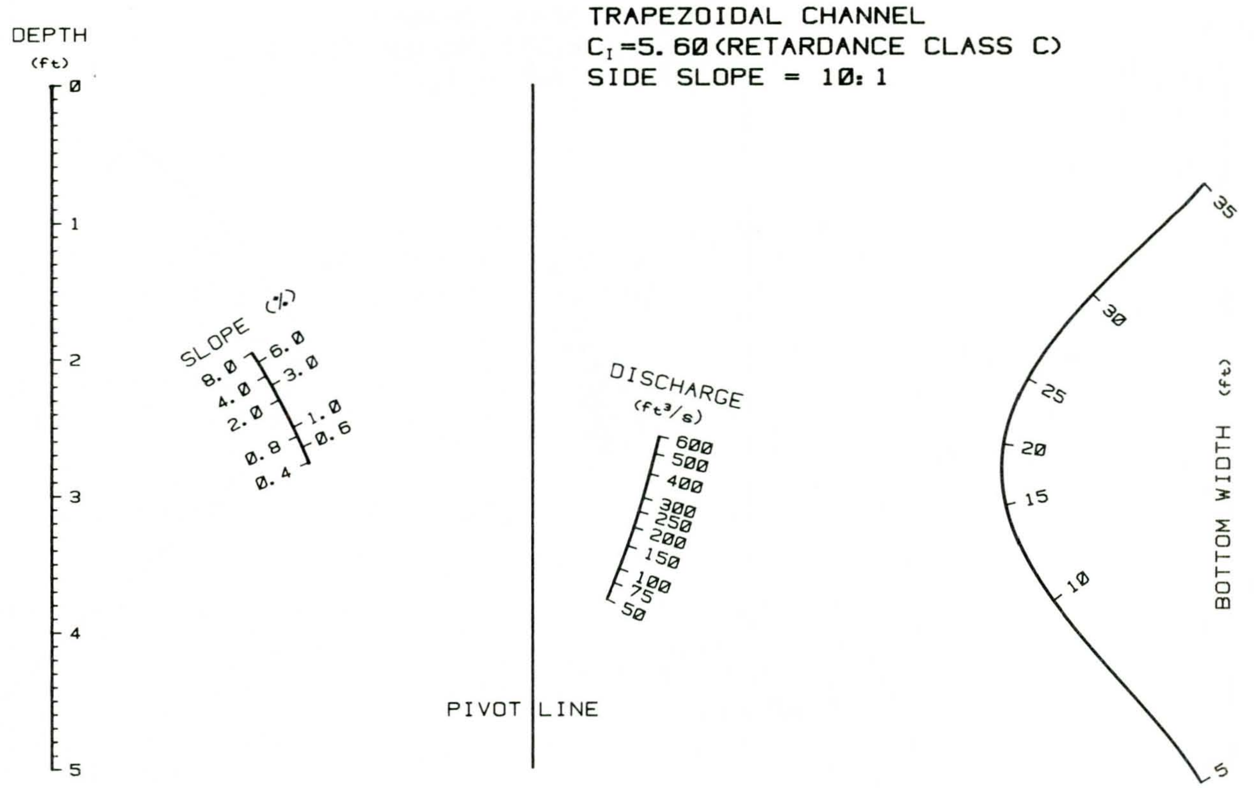

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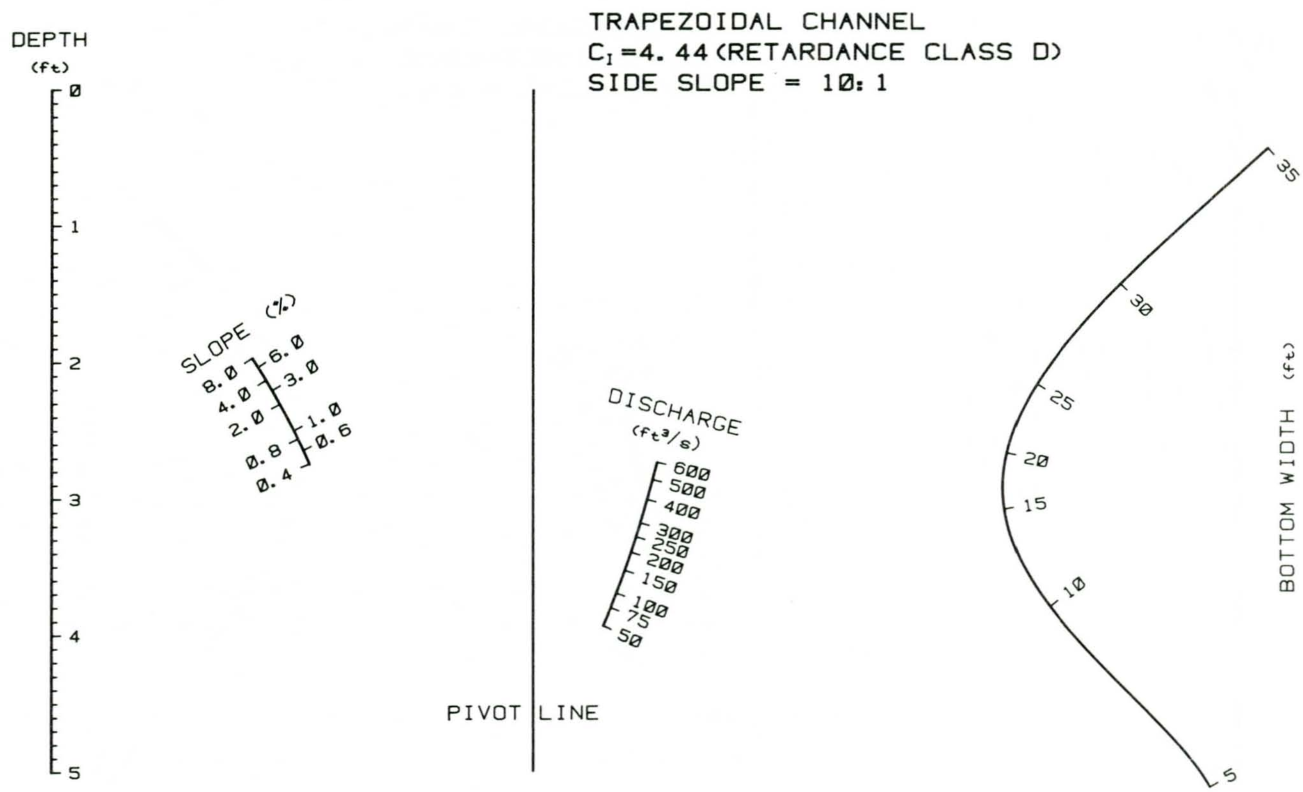

Figure 6.62

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A. VARIABLE DEFINITIONS

Variable	Definition	Dimension
A	Flow cross-sectional area	L^2
a	Locally defined coefficient or exponent	
a_p	Parabolic cross section coefficient $D=a_p(T/2)^2$	L^{-1}
B	Bed width of a trapezoidal channel	L
B_{min}	Minimum acceptable bed width of a trapezoidal channel	L
b	Locally defined coefficient or exponent	
C_F	Vegetal cover factor	
C_I	Vegetal retardance curve index	
C_e	Correction factor for soil void ratio (permissible velocity or allowable stress)	
c	Locally defined coefficient or exponent	
D	Flow depth (maximum in cross section)	L
d_{50}	Mean soil particle diameter	L
d_{75}	Soil particle diameter for which 75 percent of the material is finer	L
e	Soil void ratio	
F	Froude number	
g	Gravitational constant	LT^{-2}
h	Representative stem length of a grass lining	L
I_w	Soil plasticity index	
M	Stem density in stems per unit area	L^{-2}
n	Manning's flow resistance coefficient (for the entire channel)	
n_R	Reference value of Manning's resistance coefficient	
n_s	Manning's coefficient associated with the soil only	

Variable	Definition	Dimension
n_ψ	Manning's coefficient associated with boundary roughness elements (other than vegetation) that cannot be moved by the flow	
n_v	Manning's coefficient associated with the vegetation	
Q	Volumetric channel discharge	L^3T^{-1}
q	Volumetric discharge per unit width of wide channel	L^2T^{-1}
q_r	Locally defined coefficient	
R	Channel hydraulic radius	L
S	Energy slope	
S'	Energy slope associated with soil grain roughness	
S"	Energy slope associated with boundary form roughness	
S"'	Energy slope associated with vegetal boundary roughness	
T	Channel width at water surface	L
V	Mean velocity	LT^{-1}
V_a	Permissible velocity	LT^{-1}
V_m	Mean velocity computed by Manning's equation	LT^{-1}
v	Velocity at a point	LT^{-1}
W	Reference channel width (measured at ½ wide channel reference depth)	L
Z	Cotangent of bank slope angle (measured at water surface)	
Z_{min}	Minimum acceptable value of Z (maximum acceptable bank slope)	
α	Energy coefficient	
β	Momentum coefficient	
γ	Unit weight of water	$ML^{-2}T^{-2}$

Variable	Definition	Dimension
θ	Bed slope angle (measured from horizontal)	
τ	Gross mean boundary stress	$ML^{-1}T^{-2}$
τ_a	Allowable (effective) stress	$ML^{-1}T^{-2}$
τ_{ab}	Basic allowable effective stress (not corrected for soil void ratio)	$ML^{-1}T^{-2}$
τ_e	Erosionally effective stress at the soil boundary	$ML^{-1}T^{-2}$
τ_v	Boundary stress associated with a vegetal lining	$ML^{-1}T^{-2}$
τ_{va}	Maximum allowable vegetal stress	$ML^{-1}T^{-2}$
ν	Kinematic viscosity	

B. CALCULATOR/COMPUTER ROUTINES

Section 1

Two-Dimensional Flow Approximation for HP-97/67

STEP	KEY	CODE	STEP	KEY	CODE
001	*LBLA	21 11	031	.	-62
002	DSP4	-63 04	032	9	09
003	RCL2	36 02	033	4	04
004	.	-62	034	ST-9	35-45 09
005	2	02	035	RCL2	36 02
006	9	09	036	.	-62
007	7	07	037	0	00
008	x	-35	038	1	01
009	ST09	35 09	039	3	03
010	RCL1	36 01	040	3	03
011	$\sqrt{X}$	54	041	x	-35
012	LN	32	042	ST00	35 00
013	ST-9	35-45 09	043	RCL2	36 02
014	1	01	044	.	-62
015	RCL3	36 03	045	0	00
016	-	-45	046	9	09
017	RCL4	36 04	047	5	05
018	X^2	53	048	4	04
019	x	-35	049	x	-35
020	RCL5	36 05	050	.	-62
021	X⇄Y	-41	051	4	04
022	÷	-24	052	2	02
023	LN	32	053	9	09
024	.	-62	054	+	-55
025	7	07	055	CHS	-22
026	1	01	056	ST06	35 06
027	4	04	057	4	04
028	x	-35	058	RCL0	36 00
029	ST+9	35-55 09	059	x	-35
030	6	06	060	RCL9	36 09

STEP	KEY	CODE
061	x	-35
062	RCL6	36 06
063	X^2	53
064	X⇄Y	-41
065	-	-45
066	√X	54
067	RCL6	36 06
068	CHS	-22
069	X⇄Y	-41
070	-	-45
071	2	02
072	÷	-24
073	RCL0	36 00
074	÷	-24
075	e^X	33
076	ST06	35 06
077	*LBLB	21 12
078	DSP4	-63 04
079	RCL6	36 06
080	LN	32
081	STOI	35 46
082	X^2	53
083	.	-62
084	0	00
085	1	01
086	3	03
087	3	03
088	x	-35
089	ST09	35 09
090	RCLI	36 46
091	.	-62
092	0	00
093	9	09
094	5	05
095	4	04
096	x	-35
097	ST-9	35-45 09
098	.	-62
099	2	02
100	9	09
101	7	07
102	ST+9	35-55 09
103	RCL2	36 02
104	STx9	35-35 09
105	4	04
106	.	-62
107	1	01
108	6	06
109	ST-9	35-45 09
110	RCL9	36 09
111	e^X	33
112	P⇄S	16-51
113	ST00	35 00
114	P⇄S	16-51
115	RCL6	36 06
116	P⇄S	16-51
117	RCL0	36 00
118	P⇄S	16-51
119	x	-35
120	1	01

STEP	KEY	CODE
121	.	-62
122	4	04
123	9	09
124	÷	-24
125	RCL1	36 01
126	√X	54
127	÷	-24
128	.	-62
129	6	06
130	Y^X	31
131	STO7	35 07
132	RCL6	36 06
133	RCL7	36 07
134	÷	-24
135	STO8	35 08
136	RCL2	36 02
137	2	02
138	.	-62
139	5	05
140	Y^X	31
141	.	-62
142	0	00
143	0	00
144	2	02
145	5	05
146	x	-35
147	P⇄S	16-51
148	STO7	35 07
149	P⇄S	16-51
150	6	06

STEP	KEY	CODE
151	2	02
152	.	-62
153	4	04
154	RCL7	36 07
155	x	-35
156	RCL1	36 01
157	x	-35
158	RCL5	36 05
159	-	-45
160	P⇄S	16-51
161	STO9	35 09
162	P⇄S	16-51
163	.	-62
164	7	07
165	5	05
166	RCL2	36 02
167	x	-35
168	STO9	35 09
169	RCL6	36 06
170	RTN	24
171	R/S	51

Section 2 Two-Dimensional Flow Approximation for TI-59/58C

STEP	CODE	KEY	STEP	CODE	KEY	STEP	CODE	KEY
000	76	Lbl	025	55	÷	050	65	x
001	11	A	026	53	(	051	93	.
002	58	Fix	027	53	(	052	00	0
003	04	4	028	01	1	053	01	1
004	43	RCL	029	75	-	054	03	3
005	02	02	030	43	RCL	055	03	3
006	65	x	031	03	03	056	95	=
007	93	.	032	54	)	057	42	STO
008	02	2	033	65	x	058	00	00
009	09	9	034	43	RCL	059	43	RCL
010	07	7	035	04	04	060	02	02
011	75	-	036	33	x^2	061	65	x
012	43	RCL	037	54	)	062	93	.
013	01	01	038	54	)	063	00	0
014	34	$\sqrt{x}$	039	23	$\ln x$	064	09	9
015	23	$\ln x$	040	75	-	065	05	5
016	85	+	041	06	6	066	04	4
017	93	.	042	93	.	067	85	+
018	07	7	043	09	9	068	93	.
019	01	1	044	04	4	069	04	4
020	04	4	045	95	=	070	02	2
021	65	x	046	42	STO	071	09	9
022	53	(	047	09	09	072	95	=
023	43	RCL	048	43	RCL	073	94	+/-
024	05	05	049	02	02	074	42	STO

STEP	CODE	KEY	STEP	KEY	CODE	STEP	CODE	KEY
075	06	06	102	00	00	129	09	9
076	53	(	103	54	)	130	05	5
077	53	(	104	54	)	131	04	4
078	43	RCL	105	22	INV	132	65	x
079	06	06	106	23	ℓnx	133	53	(
080	94	+/-	107	95	=	134	43	RCL
081	75	-	108	42	STO	135	06	06
082	53	(	109	06	06	136	23	ℓnx
083	43	RCL	110	76	Lbl	137	54	)
084	06	06	111	12	B	138	85	+
085	33	x^2	112	58	Fix	139	93	.
086	75	-	113	04	4	140	02	2
087	04	4	114	53	(	141	09	9
088	65	x	115	53	(	142	07	7
089	43	RCL	116	43	RCL	143	54	)
090	00	00	117	06	06	144	65	x
091	65	x	118	23	ℓnx	145	43	RCL
092	43	RCL	119	33	x^2	146	02	02
093	09	09	120	65	x	147	75	-
094	54	)	121	93	.	148	04	4
095	34	$\sqrt{x}$	122	00	0	149	93	.
096	54	)	123	01	1	150	01	1
097	55	÷	124	03	3	151	06	6
098	53	(	125	03	3	152	54	)
099	02	2	126	75	-	153	22	INV
100	65	x	127	93	.	154	23	ℓnx
101	43	RCL	128	00	0	155	95	=

STEP	CODE	KEY
156	42	STO
157	10	10
158	53	(
159	43	RCL
160	06	06
161	65	x
162	43	RCL
163	10	10
164	55	÷
165	01	1
166	93	.
167	04	4
168	09	9
169	55	÷
170	43	RCL
171	01	01
172	34	$\sqrt{x}$
173	54	)
174	45	y^x
175	93	.
176	06	6
177	95	=
178	42	STO
179	07	07
180	43	RCL
181	06	06

STEP	CODE	KEY
182	55	÷
183	43	RCL
184	07	07
185	95	=
186	42	STO
187	08	08
188	43	RCL
189	02	02
190	45	y^x
191	02	2
192	93	.
193	05	5
194	65	x
195	93	.
196	00	0
197	00	0
198	02	2
199	05	5
200	95	=
201	42	STO
202	17	17
203	06	6
204	02	2
205	93	.
206	04	4
207	65	x

STEP	CODE	KEY
208	43	RCL
209	07	07
210	65	x
211	43	RCL
212	01	01
213	75	-
214	43	RCL
215	05	05
216	95	=
217	42	STO
218	19	19
219	93	.
220	07	7
221	05	5
222	65	x
223	43	RCL
224	02	02
225	95	=
226	42	STO
227	09	09
228	43	RCL
229	06	06
230	91	R/S
231	81	RST

Iterative Design of Trapezoidal Channels for HP-97/67

STEP	KEY	CODE	STEP	KEY	CODE
001	*LBLA	21 11	031	RCLI	36 46
002	DSP4	-63 04	032	x	-35
003	5	05	033	2	02
004	STO0	35 00	034	x	-35
005	*LBLB	21 12	035	RCL7	36 07
006	RCL6	36 06	036	+	-55
007	RCL0	36 00	037	RCL9	36 09
008	÷	-24	038	X⇄Y	-41
009	STO9	35 09	039	÷	-24
010	RCL8	36 08	040	RCLI	36 46
011	x	-35	041	RCL9	36 09
012	4	04	042	P⇄S	16-51
013	x	-35	043	STO0	35 00
014	RCL7	36 07	044	R↓	-31
015	X^2	53	045	STO3	35 03
016	+	-55	046	R↓	-31
017	$\sqrt{X}$	54	047	STO1	35 01
018	RCL7	36 07	048	P⇄S	16-51
019	CHS	-22	049	RCL0	36 00
020	+	-55	050	x	-35
021	2	02	051	STOE	35 15
022	÷	-24	052	LN	32
023	RCL8	36 08	053	STOI	35 46
024	÷	-24	054	X^2	53
025	STOI	35 46	055	.	-62
026	RCL8	36 08	056	0	00
027	X^2	53	057	1	01
028	1	01	058	3	03
029	+	-55	059	3	03
030	$\sqrt{X}$	54	060	x	-35

STEP	KEY	CODE	STEP	KEY	CODE
061	RCLI	36 46	091	9	09
062	.	-62	092	x	-35
063	0	00	093	RCL1	36 01
064	9	09	094	P⇄S	16-51
065	5	05	095	2	02
066	4	04	096	ENTER	-21
067	x	-35	097	3	03
068	-	-45	098	÷	-24
069	.	-62	099	Y^X	31
070	2	02	100	x	-35
071	9	09	101	RCL1	36 01
072	7	07	102	$\sqrt{X}$	54
073	+	-55	103	x	-35
074	RCL2	36 02	104	P⇄S	16-51
075	x	-35	105	STO4	35 04
076	4	04	106	P⇄S	16-51
077	.	-62	107	RCL0	36 00
078	1	01	108	-	-45
079	6	06	109	ABS	16 31
080	-	-45	110	.	-62
081	e^X	33	111	0	00
082	RCLE	36 15	112	0	00
083	P⇄S	16-51	113	1	01
084	STO6	35 06	114	-	-45
085	R↓	-31	115	X<0?	16-45
086	STO2	35 02	116	GTOC	22 13
087	1/X	52	117	P⇄S	16-51
088	1	01	118	RCL4	36 04
089	.	-62	119	P⇄S	16-51
090	4	04	120	RCL0	36 00

STEP	KEY	CODE	STEP	KEY	CODE
121	-	-45	151	x	-35
122	.	-62	152	P⇄S	16-51
123	6	06	153	ST08	35 08
124	7	07	154	P⇄S	16-51
125	x	-35	155	RCL9	36 09
126	RCL0	36 00	156	RCL1	36 01
127	+	-55	157	x	-35
128	ST00	35 00	158	P⇄S	16-51
129	GTOB	22 12	159	RCL3	36 03
130	*LBLC	21 13	160	x	-35
131	1	01	161	RCL8	36 08
132	RCL3	36 03	162	-	-45
133	-	-45	163	ST09	35 09
134	RCL1	36 01	164	RCL3	36 03
135	x	-35	165	P⇄S	16-51
136	6	06	166	RCL8	36 08
137	2	02	167	x	-35
138	.	-62	168	2	02
139	4	04	169	x	-35
140	ST09	35 09	170	RCL7	36 07
141	x	-35	171	+	-55
142	P⇄S	16-51	172	P⇄S	16-51
143	RCL3	36 03	173	ST05	35 05
144	x	-35	174	P⇄S	16-51
145	RCL2	36 02	175	RCL2	36 02
146	X^2	53	176	2	02
147	÷	-24	177	.	-62
148	P⇄S	16-51	178	5	05
149	RCL4	36 04	179	Y^X	31
150	X^2	53	180	.	-62

STEP	KEY	CODE
181	0	00
182	0	00
183	2	02
184	5	05
185	x	-35
186	P⇄S	16-51
187	STO7	35 07
188	P⇄S	16-51
189	.	-62
190	7	07
191	5	05
192	RCL2	36 02
193	x	-35
194	STO9	35 09
195	RCL5	36 05
196	P⇄S	16-51
197	RCL8	36 08
198	P⇄S	16-51
199	-	-45
200	RTN	24
201	R/S	51

Iterative Design of Trapezoidal Channels for TI-59/58C

STEP	CODE	KEY	STEP	CODE	KEY	STEP	CODE	KEY
000	76	Lbl	025	33	x^2	050	07	07
001	11	A	026	85	+	051	85	+
002	58	Fix	027	04	4	052	02	2
003	04	4	028	65	x	053	65	x
004	05	5	029	43	RCL	054	43	RCL
005	42	STO	030	10	10	055	13	13
006	00	00	031	65	x	056	65	x
007	76	Lbl	032	43	RCL	057	53	(
008	12	B	033	08	08	058	43	RCL
009	43	RCL	034	54	)	059	08	08
010	06	06	035	34	$\sqrt{x}$	060	33	x^2
011	55	÷	036	54	)	061	85	+
012	43	RCL	037	55	÷	062	01	1
013	00	00	038	02	2	063	54	)
014	95	=	039	55	÷	064	34	$\sqrt{x}$
015	42	STO	040	43	RCL	065	54	)
016	10	10	041	08	08	066	95	=
017	53	(	042	95	=	067	42	STO
018	43	RCL	043	42	STO	068	11	11
019	07	07	044	13	13	069	65	x
020	94	+/-	045	43	RCL	070	43	RCL
021	85	+	046	10	10	071	00	00
022	53	(	047	55	÷	072	95	=
023	43	RCL	048	53	(	073	42	STO
024	07	07	049	43	RCL	074	16	16

STEP	CODE	KEY
075	23	ℓnx
076	42	STO
077	09	09
078	53	(
079	53	(
080	43	RCL
081	09	09
082	33	x^2
083	65	x
084	93	.
085	00	0
086	01	1
087	03	3
088	03	3
089	75	-
090	43	RCL
091	09	09
092	65	x
093	93	.
094	00	0
095	09	9
096	05	5
097	04	4
098	85	+
099	93	.
100	02	2
101	09	9
102	07	7
103	54	)
104	65	x
105	43	RCL
106	02	02
107	75	-
108	04	4
109	93	.
110	01	1
111	06	6
112	54	)
113	22	INV
114	23	ℓnx
115	95	=
116	42	STO
117	12	12
118	01	1
119	93	.
120	04	4
121	09	9
122	65	x
123	43	RCL
124	11	11
125	45	y^x
126	53	(
127	02	2
128	55	÷
129	03	3
130	54	)
131	65	x
132	43	RCL
133	01	01
134	34	$\sqrt{x}$
135	55	÷
136	43	RCL
137	12	12
138	95	=
139	42	STO
140	14	14
141	93	.
142	00	0
143	00	0
144	01	1
145	32	x⇄t
146	53	(
147	43	RCL
148	14	14
149	75	-

STEP	CODE	KEY	STEP	CODE	KEY	STEP	CODE	KEY
150	43	RCL	175	12	B	200	06	6
151	00	00	176	76	Lbl	201	02	2
152	54	)	177	13	C	202	93	.
153	50	$\|x\|$	178	53	(	203	04	4
154	22	INV	179	43	RCL	204	42	STO
155	77	$x \geq t$	180	04	04	205	09	09
156	13	C	181	55	÷	206	95	=
157	53	(	182	43	RCL	207	42	STO
158	43	RCL	183	12	12	208	18	18
159	14	14	184	54	)	209	43	RCL
160	75	-	185	33	x^2	210	09	09
161	43	RCL	186	65	x	211	65	x
162	00	00	187	53	(	212	43	RCL
163	54	)	188	01	1	213	13	13
164	65	x	189	75	-	214	65	x
165	93	.	190	43	RCL	215	43	RCL
166	06	6	191	03	03	216	01	01
167	07	7	192	54	)	217	75	-
168	85	+	193	65	x	218	43	RCL
169	43	RCL	194	43	RCL	219	18	18
170	00	00	195	01	01	220	95	=
171	95	=	196	65	x	221	42	STO
172	42	STO	197	43	RCL	222	19	19
173	00	00	198	13	13	223	02	2
174	61	GTO	199	65	x	224	65	x

STEP	CODE	KEY
225	43	RCL
226	08	08
227	65	x
228	43	RCL
229	13	13
230	85	+
231	43	RCL
232	07	07
233	95	=
234	42	STO
235	15	15
236	43	RCL
237	02	02
238	45	y^x
239	02	2
240	93	.
241	05	5
242	65	x
243	93	.
244	00	0
245	00	0
246	02	2
247	05	5
248	95	=
249	42	STO
250	17	17
251	93	.
252	07	7
253	05	5
254	65	x
255	43	RCL
256	02	02
257	95	=
258	42	STO
259	09	09
260	43	RCL
261	05	05
262	75	-
263	43	RCL
264	18	18
265	95	=
266	91	R/S
267	81	RST

Iterative Design of Parabolic Channels for HP-97/67

STEP	KEY	CODE	STEP	KEY	CODE
001	*LBLA	21 11	031	1	01
002	DSP4	-63 04	032	+	-55
003	5	05	033	√X	54
004	STO0	35 00	034	+	-55
005	*LBLB	21 12	035	LN	32
006	RCL6	36 06	036	2	02
007	RCL0	36 00	037	÷	-24
008	÷	-24	038	RCL7	36 07
009	STO9	35 09	039	÷	-24
010	RCL7	36 07	040	RCLI	36 46
011	√X	54	041	X^2	53
012	RCL9	36 09	042	4	04
013	x	-35	043	x	-35
014	.	-62	044	RCLI	36 46
015	7	07	045	RCL7	36 07
016	5	05	046	÷	-24
017	x	-35	047	+	-55
018	2	02	048	√X	54
019	ENTER	-21	049	+	-55
020	3	03	050	RCL9	36 09
021	÷	-24	051	X⇄Y	-41
022	Y^X	31	052	÷	-24
023	STOI	35 46	053	RCLI	36 46
024	RCL7	36 07	054	RCL9	36 09
025	x	-35	055	P⇄S	16-51
026	4	04	056	STO0	35 00
027	x	-35	057	R↓	-31
028	STO8	35 08	058	STO3	35 03
029	√X	54	059	R↓	-31
030	RCL8	36 08	060	STO1	35 01

STEP	KEY	CODE	STEP	KEY	CODE
061	P⇄S	16-51	091	1	01
062	RCL0	36 00	092	6	06
063	x	-35	093	-	-45
064	STOE	35 15	094	e^X	33
065	LN	32	095	RCLE	36 15
066	STOI	35 46	096	P⇄S	16-51
067	X^2	53	097	STO6	35 06
068	.	-62	098	R↓	-31
069	0	00	099	STO2	35 02
070	1	01	100	1/X	52
071	3	03	101	1	01
072	3	03	102	.	-62
073	x	-35	103	4	04
074	RCLI	36 46	104	9	09
075	.	-62	105	x	-35
076	0	00	106	RCL1	36 01
077	9	09	107	P⇄S	16-51
078	5	05	108	2	02
079	4	04	109	ENTER	-21
080	x	-35	110	3	03
081	-	-45	111	÷	-24
082	.	-62	112	Y^X	31
083	2	02	113	x	-35
084	9	09	114	RCL1	36 01
085	7	07	115	$\sqrt{X}$	54
086	+	-55	116	x	-35
087	RCL2	36 02	117	P⇄S	16-51
088	x	-35	118	STO4	35 04
089	4	04	119	P⇄S	16-51
090	.	-62	120	RCL0	36 00

STEP	KEY	CODE
121	-	-45
122	ABS	16 31
123	.	-62
124	0	00
125	0	00
126	1	01
127	-	-45
128	X<0?	16-45
129	GTOC	22 13
130	P⇄S	16-51
131	RCL4	36 04
132	P⇄S	16-51
133	RCL0	36 00
134	-	-45
135	.	-62
136	6	06
137	7	07
138	x	-35
139	RCL0	36 00
140	+	-55
141	STO0	35 00
142	GTOB	22 12
143	*LBLC	21 13
144	1	01
145	RCL3	36 03
146	-	-45
147	RCL1	36 01
148	x	-35
149	6	06
150	2	02
151	.	-62
152	4	04
153	STO9	35 09
154	x	-35
155	P⇄S	16-51
156	RCL3	36 03
157	x	-35
158	RCL2	36 02
159	X^2	53
160	÷	-24
161	P⇄S	16-51
162	RCL4	36 04
163	X^2	53
164	x	-35
165	P⇄S	16-51
166	STO8	35 08
167	P⇄S	16-51
168	RCL9	36 09
169	RCL1	36 01
170	x	-35
171	P⇄S	16-51
172	RCL3	36 03
173	x	-35
174	RCL8	36 08
175	-	-45
176	STO9	35 09
177	RCL0	36 00
178	3	03
179	x	-35
180	RCL3	36 03

STEP	KEY	CODE
181	÷	-24
182	2	02
183	÷	-24
184	STO5	35 05
185	P⇄S	16-51
186	RCL2	36 02
187	2	02
188	.	-62
189	5	05
190	Y^X	31
191	.	-62
192	0	00
193	0	00
194	2	02
195	5	05
196	x	-35
197	P⇄S	16-51
198	STO7	35 07
199	P⇄S	16-51
200	.	-62
201	7	07
202	5	05
203	RCL2	36 02
204	x	-35
205	STO9	35 09
206	RCL5	36 05
207	P⇄S	16-51
208	RCL8	36 08
209	P⇄S	16-51
210	-	-45

STEP	KEY	CODE
211	RTN	24
212	R/S	51

Section 6 Iterative Design for Parabolic Channels for TI-59/58C

STEP	CODE	KEY	STEP	CODE	KEY	STEP	CODE	KEY
000	76	Lbl	025	53	(	050	13	13
001	11	A	026	43	RCL	051	33	x^2
002	58	Fix	027	07	07	052	85	+
003	04	4	028	54	)	053	43	RCL
004	05	5	029	45	y^x	054	13	13
005	42	STO	030	93	.	055	55	÷
006	00	00	031	05	5	056	43	RCL
007	76	Lbl	032	54	)	057	07	07
008	12	B	033	45	y^x	058	54	)
009	43	RCL	034	53	(	059	34	$\sqrt{x}$
010	06	06	035	02	2	060	85	+
011	55	÷	036	55	÷	061	93	.
012	43	RCL	037	03	3	062	05	5
013	00	00	038	54	)	063	55	÷
014	95	=	039	95	=	064	43	RCL
015	42	STO	040	42	STO	065	07	07
016	10	10	041	13	13	066	65	x
017	53	(	042	43	RCL	067	53	(
018	93	.	043	10	10	068	53	(
019	07	7	044	55	÷	069	04	4
020	05	5	045	53	(	070	65	x
021	65	x	046	53	(	071	43	RCL
022	43	RCL	047	04	4	072	07	07
023	10	10	048	65	x	073	65	x
024	65	x	049	43	RCL	074	43	RCL

STEP	CODE	KEY	STEP	CODE	KEY	STEP	CODE	KEY
075	13	13	100	95	=	125	04	4
076	54	)	101	42	STO	126	85	+
077	34	$\sqrt{x}$	102	16	16	127	93	.
078	85	+	103	23	$\ell n x$	128	02	2
079	53	(	104	42	STO	129	09	9
080	04	4	105	09	09	130	07	7
081	65	x	106	53	(	131	54	)
082	43	RCL	107	53	(	132	65	x
083	07	07	108	43	RCL	133	43	RCL
084	65	x	109	09	09	134	02	02
085	43	RCL	110	33	x^2	135	75	-
086	13	13	111	65	x	136	04	4
087	85	+	112	93	.	137	93	.
088	01	1	113	00	0	138	01	1
089	54	)	114	01	1	139	06	6
090	34	$\sqrt{x}$	115	03	3	140	54	)
091	54	)	116	03	3	141	22	INV
092	23	$\ell n x$	117	75	-	142	23	$\ell n x$
093	54	)	118	43	RCL	143	95	=
094	95	=	119	09	09	144	42	STO
095	42	STO	120	65	x	145	12	12
096	11	11	121	93	.	146	01	1
097	65	x	122	00	0	147	93	.
098	43	RCL	123	09	9	148	04	4
099	00	00	124	05	5	149	09	9

STEP	CODE	KEY
150	65	x
151	43	RCL
152	11	11
153	45	y^x
154	53	(
155	02	2
156	55	÷
157	03	3
158	54	)
159	65	x
160	43	RCL
161	01	01
162	34	$\sqrt{x}$
163	55	÷
164	43	RCL
165	12	12
166	95	=
167	42	STO
168	14	14
169	93	.
170	00	0
171	00	0
172	01	1
173	32	$x \rightleftarrows t$
174	53	(

STEP	CODE	KEY
175	43	RCL
176	14	14
177	75	-
178	43	RCL
179	00	00
180	54	)
181	50	$\|x\|$
182	22	INV
183	77	$x \geq t$
184	13	C
185	53	(
186	43	RCL
187	14	14
188	75	-
189	43	RCL
190	00	00
191	54	)
192	65	x
193	93	.
194	06	6
195	07	7
196	85	+
197	43	RCL
198	00	00
199	95	=

STEP	CODE	KEY
200	42	STO
201	00	00
202	61	GTO
203	12	B
204	76	Lbl
205	13	C
206	53	(
207	43	RCL
208	04	04
209	55	÷
210	43	RCL
211	12	12
212	54	)
213	33	x^2
214	65	x
215	53	(
216	01	1
217	75	-
218	43	RCL
219	03	03
220	54	)
221	65	x
222	43	RCL
223	01	01
224	65	x

STEP	CODE	KEY
225	43	RCL
226	13	13
227	65	x
228	06	6
229	02	2
230	93	.
231	04	4
232	42	STO
233	09	09
234	95	=
235	42	STO
236	18	18
237	43	RCL
238	09	09
239	65	x
240	43	RCL
241	13	13
242	65	x
243	43	RCL
244	01	01
245	75	-
246	43	RCL
247	18	18
248	95	=
249	42	STO

STEP	CODE	KEY
250	19	19
251	03	3
252	65	x
253	43	RCL
254	10	10
255	55	÷
256	02	2
257	55	÷
258	43	RCL
259	13	13
260	95	=
261	42	STO
262	15	15
263	43	RCL
264	02	02
265	45	y^x
266	02	2
267	93	.
268	05	5
269	65	x
270	93	.
271	00	0
272	00	0
273	02	2
274	05	5

STEP	CODE	KEY
275	95	=
276	42	STO
277	17	17
278	93	.
279	07	7
280	05	5
281	65	x
282	43	RCL
283	02	02
284	95	=
285	42	STO
286	09	09
287	43	RCL
288	05	05
289	75	-
290	43	RCL
291	18	18
292	95	=
293	91	R/S
294	81	RST

```
10   DIM COE(4),SOC$(14),ALCO(5,4),FLAG(5)
20   FOR II=1 TO 4: READ COE(II): NEXT II                    'n-VR curve coefficients
30   DATA .0133,-.0954,.297,-4.16
40   FOR II=1 TO 14: READ SOC$(II): NEXT II                  'Soil types from the
unified soil classification system
50   DATA GC,GM,SC,SM,ML,CL,OL,MH,CH,OH,GW,SW,GP,SP
60   FOR II=1 TO 5: FOR JJ=1 TO 4: READ ALCO(II,JJ): NEXT JJ,II    'Coefficient
matrix for energy coefficient estimation
70   DATA 4.31,-9.19,1.99,1.57
80   DATA 0.23,-0.0216,0.178,-.000932
90   DATA -0.0177,0.00857,0.00159,0.00364
100  DATA 0.000155,0.000815,-0.00114,-0.000283
110  DATA 0.0298,0.0833,0.00796,-.000359
120  SLIN$="P"                     'Default soil data input code
130  NS=.0156                      'Default soil grain roughness
140  CIF$="LD"                     'Default vegetal data input code
150  AU=1.49                       'Unit dependent constant of Manning's eq.
160  WSPW=62.4                     'Unit weight of water
170  GR=32.2                       'Gravitational constant
180  CSEQ=-6.94                    'Unit dependent constant
190  '
200  ' This routine is written for the IBM-PC using Microsoft BASIC.
210  '
220  ' GRASS LINED CHANNEL DESIGN BY TRACTIVE FORCE CONCEPTS: REVISED  3-85
230  '
240  '   This program uses the effective stress procedure for grass-lined
250  ' channel design presented in the Handbook for the Design of Grass-lined
260  ' Open Channels.  Although the approach is that of tractive force,
270  ' computation of the actual forces on the individual particles or
280  ' aggregates capable of being detached is impractical.  Practical
290  ' application of the tractive force concepts results in a procedure
300  ' using erosionally effective stress as the governing stability
310  ' parameter.  Hence, an effective stress design procedure.
320  '
330  '  This routine combines a numerical form of the Soil Conservation Service
340  ' channel stability criteria converted to an effective stress format and
350  ' a numerical flow resistance - Reynolds No. relation similar to the SCS
360  ' n-VR curves with Manning's equation, an erosionally effective stress
370  ' relation, and the geometric relations for the common open channel
380  ' shapes (trapezoidal, triangular, and parabolic).
390  '
400  '     Although  several checks and warnings are incorporated into this
410  ' routine, it should be considered as an equation solver and NOT as a
420  ' substitute for the engineering judgement required by the present state
430  ' of the art in this area.  Output from the routine should be treated
440  ' accordingly.
450  '
460 'PRINT STATEMENT ADDRESS TO CRT
470 CLS: PRINT TAB(20);"EFFECTIVE STRESS DESIGN OF GRASS-LINED CHANNELS"
480 PRINT "                          (DIRECT DESIGN ROUTINE) "
490 PRINT "                           ENGLISH UNIT VERSION";TAB(2)
500 ' CHANNEL GEOMETRY INPUT
510 PRINT
520 PRINT
```

```
530 PRINT
540 PRINT "                         ENTER CROSS-SECTIONAL SHAPE  "
550 PRINT "                         TRAPEZOIDAL ------------ 'T'"
560 PRINT "                         TRIANGULAR ------------- 'TR'"
570 PRINT "                         PARABOLIC -------------- 'P'"
580 INPUT "                                        ";CTYPE$
590 PRINT TAB(0);"                                                          "
600 IF CTYPE$="T" THEN 720
610 IF CTYPE$="TR" THEN 760
620 IF CTYPE$="P" THEN 800
630 IF CTYPE$="TRAPEZOIDAL" THEN 720
640 IF CTYPE$="TRIANGULAR" THEN 760
650 IF CTYPE$="PARABOLIC" THEN 800
660 CLS
670 PRINT CTYPE$;" X-SECTION SHAPE NOT RECOGNIZED; PLEASE RE-ENTER.";
680 PRINT
690 PRINT
700 PRINT
710 GOTO 540
720 CTYP=1
730 CTYPE$="TRAPEZOIDAL"
740 LPARM$="BED WIDTH"
750 GOTO 830
760 CTYP=2
770 CTYPE$="TRIANGULAR"
780 LPARM$="SIDE SLOPE"
790 GOTO 830
800 CTYP=3
810 CTYPE$="PARABOLIC"
820 LPARM$="MAX SIDE SLOPE"
830 INPUT "INPUT CHANNEL BED SLOPE";S
840 IF CTYP<>1 THEN 890
850 INPUT "ENTER COTANGENT OF BANK SIDE SLOPE ";Z
860 INPUT "ENTER LIMITING MINIMUM BED WIDTH (DEFAULT APPROXIMATES MIN. FLOW
AREA)";BMIN
870 IF BMIN=0 THEN BMIN=-1
880 GOTO 910
890 INPUT "ENTER LIMITING MINIMUM COTANGENT OF BANK SLOPE (DEFAULT = 2 ie; 2:1
)";ZMIN
900  IF ZMIN=0  THEN ZMIN=2
910  CLS:FOR X = 1 TO 7 :PRINT:NEXT
920  ' CHANNEL BOUNDARY MATERIAL INFORMATION
930  PRINT "            SOIL SURFACE LAYER INFORMATION"
940  PRINT TAB(1);"OPTIONS AVAILABLE FOR ENTRY OF SOIL ERODIBILITY"
950  PRINT TAB(1);"        OPTION
CODE"
960  PRINT "    Basic soil PROPERTIES   (plasticity, density, gradation)      P"
970  PRINT "    Allowable effective STRESS  plus soil grain roughness         S"
980  PRINT "    Reference bare soil permissible VELOCITY                      V"
990 INPUT "ENTER INPUT OPTION (Default = 'P')";SLIN$
1000 IF SLIN$="S" THEN 1470
1010 IF SLIN$="V" THEN 1510
1020 PRINT TAB(1);" Soil types from unified soil classification system"
Uses equations of handbook Table 3.3
```

```
1030 PRINT "Do not use double classifications such as CL-ML"
1040 INPUT "SURFACE SOIL CLASSIFICATION ";SOIL$
1050 ISL=1                                  'Numerical soil type identifier
1060 IF SOC$(ISL) = SOIL$ THEN 1100
1070 ISL=ISL+1
1080 IF ISL<15 THEN 1060
1090 PRINT "SOIL TYPE ";SOIL$;" NOT RECOGNIZED; COARSE GRAINED SOIL ASSUMED FOR
REACH";I;TAB(0);
1100 IF ISL>10 THEN 1150
1110 INPUT "PLASTICITY INDEX";IW                        'Fine grained soil
1120 IWC=IW
1130 INPUT "ENTER VOID RATIO (default is to a void ratio correction of 1.0)";EV
1140 IF IW>=10 THEN 1220
1150 INPUT " GRAIN DIAMETER IN INCHES";D75      'Non-cohesive soil
1160 D75C=D75
1170 IF D75<.05 THEN D75C=.05                   'Fine grained soil
1180 ' DETERMINATION OF SOIL GRAIN ROUGHNESS AND ALLOWABLE EFFECTIVE TRACTIVE
STRESS
1190 NS=D75C^(1/6)/39               ' Soil grain roughness
1200 TA=.4*D75C                     ' Allowable effective stress
1210 GOTO 1340
1220 NS=.0156                       ' Assumes particle detachment of fine material
(less than 0.05") dominates stability
1230 IF IW>20 THEN IWC=20
1240 ON ISL GOTO 1250,1270,1270,1290,1290,1270,1290,1310,1330,1310
1250 TA=.0000477*IWC*IWC+.00286*IWC+.0429  'GC soil
1260 GOTO 1340
1270 TA=.000107*IWC*IWC+.00143*IWC+.00477  'GM, CL, & SC soils
1280 GOTO 1340
1290 TA=.000107*IWC*IWC+.000715*IWC+.00119 'ML, OL, & SM soils
1300 GOTO 1340
1310 TA=.0000477*IWC*IWC+.00143*IWC+.0107 'MH & OH soils
1320 GOTO 1340
1330 TA=9.660001E-02                       'CH Soil
1340 IF EV=0 THEN 1440
1350 ON ISL GOTO
1370,1370,1370,1370,1390,1390,1440,1420,1420,1440,1440,1440,1440,1440
1360 ' VOID RATIO CORRECTION
1370 CE=1.42-.61*EV                         'GM, SC, GC, & SM soils
1380 GOTO 1450
1390 CE=1.48-.57*EV                         'CL & ML soils
1400 PRINT CE
1410 GOTO 1450
1420 CE=1.38-.373*EV                        'CH & MH soils
1430 GOTO 1450
1440 CE=1                                   'All other soils
1450 TA=TA*CE*CE
1460 GOTO 1540
1470 INPUT "ENTER ALLOWABLE EFFECTIVE STRESS (lb/sq. ft)";TA
1480 INPUT "ENTER SOIL GRAIN ROUGHNESS(Default = 0.0156; fine-grained soil)";NS
1490 IF NS=0 THEN NS=.0156
1500 GOTO 1540
1510 INPUT "ENTER REFERENCE PERMISSIBLE VELOCITY in ft/s";VA
1520 TA=19.6*VA*VA*NS*NS                    'Handbook equation 1.16
```

```
1530 ' VEGETAL COVER INFORMATION
1540 CLS:FOR X = 1 TO 7 :PRINT:NEXT
1550 PRINT "                    BOUNDARY COVER INFORMATION "
1560 INPUT "TYPE OF COVER (descriptive name)";COVER$
1570 PRINT "THE FLOW RETARDANCE POTENTIAL OF THE VEGETATION MAY BE ENTERED AS;"
1580 PRINT "              Stem length and density data                LD"
1590 PRINT "              SCS retardance class                        SCS"
1600 PRINT "              Direct input of the retardance Curve Index  DI"
1610 INPUT "MEANS OF ESTIMATING VEGETAL FLOW RETARDANCE (LD, SCS, or DI)";CIF$
1620 CIIC$="STABILITY"
1630 ' ENTRY REPEATED FOR CAPACITY AND STABILITY ENTRIES
1640 PRINT "              ENTER COVER CONDITIONS FOR "CIIC$" CALCULATIONS"
1650 IF CIF$="LD" THEN 1770
1660 IF CIF$="DI" THEN 1750
1670 INPUT "RETARDANCE CLASS ";RC$
1680 ' HANDBOOK TABLE 3.2
1690 IF RC$="A" THEN CI=10
1700 IF RC$="B" THEN CI=7.64
1710 IF RC$="C" THEN CI=5.6
1720 IF RC$="D" THEN CI=4.44
1730 IF RC$="E" THEN CI=2.88
1740 GOTO 1800
1750 INPUT "CURVE INDEX ";CI
1760 GOTO 1800
1770 INPUT "STEM LENGTH (ft)";GH
1780 INPUT "STEM DENSITY (stems/sq.ft)";SC
1790 CI=2.5*(GH*SQR(SC))^(1/3)                 'Handbook equation 1.3
1800 TVA=.75*CI               'Allowable vegetal stress; Handbook equation 1.17
1810 IF TVA<TA THEN TVA=TA     'Vegetal cover not controlling factor
1820 FLAG(4)=0
1830 IF CI<2 THEN FLAG(4)=1
1840 IF CIIC$="STABILITY" THEN 1910
1850 PRINT
1860 ' INITIAL VELOCITY FOR CAPACITY CALCULATIONS
1870 GOSUB 5330
1880 R=(MANN*RV/(AU*SQR(S)))^.6
1890 V=RV/R
1900 GOTO 3420
1910 INPUT "VEGETAL COVER FACTOR ";CF
1920 PRINT
1930 INPUT "CHANNEL DISCHARGE  (cfs) ";Q
1940 CLS:FOR X = 1 TO 7 :PRINT:NEXT
1950 PRINT "INPUT DATA FOR ";CTYPE$;" CHANNEL"
1960 PRINT "   CHANNEL BED SLOPE =";S;" ft/ft";TAB(1);"   DESIGN DISCHARGE =";Q;"
cfs"
1970 IF CTYP<>1 THEN 2010
1980 IF BMIN>0 THEN PRINT "   MINIMUM BED WIDTH OF";BMIN;" ft"
1990 PRINT "   BANK SIDE SLOPES OF ";Z;":1"
2000 GOTO 2020
2010 PRINT "   BANK SLOPES NOT STEEPER THAN ";ZMIN;":1"
2020 IF SLIN$="S" THEN 2100
2030 IF SLIN$="V" THEN 2130
2040 PRINT "SOIL BOUNDARY IS CLASSIFIED AS ";SOIL$;" BY UNIFIED SOIL
CLASSIFICATION"
```

```
2050 IF ISL>10 THEN 2080
2060 PRINT "   PLASTICITY INDEX = ";IW
2070 IF EV<>0 THEN PRINT "   VOID RATIO = ";EV
2080 IF D75>0 THEN PRINT "   d75 OF THE SOIL = ";D75;" inches"
2090 GOTO 2140
2100 PRINT "ALLOWABLE EFFECTIVE SOIL STRESS =";TA;" lb/sq.ft"
2110 PRINT "MANNING'S COEFFICIENT ASSOCIATED WITH THE SOIL =";NS
2120 GOTO 2140
2130 PRINT "REFERENCE PERMISSIBLE VELOCITY FOR THE SOIL =";VA;" ft/s"
2140 PRINT COVER$;" VEGETAL COVER"
2150 IF CIF$="LD" THEN PRINT "   STEM LENGTH =";GH;" ft";TAB(1);"   STEM DENSITY
=";SC;" stems/ft/ft"
2160 IF CIF$="SCS" THEN PRINT "   SCS RETARDANCE  CLASS   " RC$
2170 IF CIF$="DI" THEN PRINT "   RETARDANCE CURVE INDEX = ";CI
2180 PRINT "   VEGETAL COVER FACTOR = ";CF
2190 INAN$="OK"
2200 FOR X = 1 TO 5:PRINT:NEXT
2210 PRINT"IF DATA IS CORRECT HIT ANY KEY TO CONTINUE, IF NOT HIT'C'TO CORRECT"
2220 A$=INKEY$ :IF A$ = "" THEN 2220
2230 CLS
2240 IF A$ = "C" THEN 460
2250 ' WIDE CHANNEL (2-D FLOW) ASSUMPTION  FOR STABILITY
2260 AQU=CI*COE(1)
2270 BQU=CI*COE(2)-3/7
2280 CQU=CI*COE(3)-1/2*LOG(S)+5/7*LOG(TA/((1-CF)*NS*NS))+CSEQ
2290 BSMFAC=BQU*BQU-4*AQU*CQU
2300 IF BSMFAC<0 THEN 2330
2310 QUW=EXP((-BQU-SQR(BSMFAC))/(2*AQU))          'Limiting unit discharge
2320 RV=QUW
2330 GOSUB 5330
2340 ESN=DVV
2350 IF RV>36 THEN 2390                          'n-VR curve check and adjustment
2360 IF RV<.0025*CI^2.5 THEN 2390
2370 EDPT=(QUW*ESN/(AU*SQR(S)))^.6               'Wide channel depth
2380 GOTO 2420
2390 EDPT=TA*ESN*ESN/(WSPW*S*(1-CF)*NS*NS)
2400 QUW=AU*EDPT^(5/3)*SQR(S)/ESN
2410 RV=QUW
2420 EMWD=Q/QUW
2430 W=EMWD                                      'Channel width at 1/2 Edpt
2440 EMVE=QUW/EDPT
2450 V=EMVE                                      'Estimated mean velocity
2460 ON CTYP GOTO 2470,2560,2620
2470 ' CHECK OF LIMITING GEOMETRY
2480 B=W-Z*EDPT                                  'Trapezoidal channel bed width
2490 BS=BMIN
2500 IF BS<0 THEN BS=0
2510 IF B>BS THEN 2690
2520 B=BS
2530 ISAL=ISAL+1                  'Geometric limit loop iteration counter
2540 W=B+Z*EDPT
2550 GOTO 2690
2560 Z=W/EDPT                     'Triangular channel bank slope
2570 IF Z>=ZMIN THEN 2690
```

```
2580 Z=ZMIN
2590 ISAL=ISAL+1
2600 W=Z*EDPT
2610 GOTO 2690
2620 AA=2*EDPT/W/W                    'Parabolic channel cross section coefficient
2630 Z=W/(EDPT*SQR(8))
2640 IF Z>=ZMIN THEN 2690
2650 Z=ZMIN
2660 ISAL=ISAL+1
2670 W=Z*EDPT*SQR(8)
2680 AA=0
2690 JD1=0
2700 A=Q/V                                    'Flow X-section area
2710 GOSUB 5470                               'Flow depth
2720 GOSUB 5580                               'Wetted perimeter
2730 R=A/P                                    'Hydraulic radius
2740 RV=V*R
2750 GOSUB 5330
2760 MANN=DVV
2770 VM=AU/MANN*R^(2/3)*SQR(S)                'Computed velocity
2780 VADJ=2*(VM-V)/3                          'Velocity adjustment
2790 IF ABS(VADJ/VM)<.001 THEN 2850           'Velocity convergence check
2800 JD1=JD1+1                                'Iteration loop counter
2810 V=V+VADJ                                 'New velocity estimate
2820 IF JD1<30 THEN 2700
2830 PRINT "ITERATIVE CONVERGENCE FAILURE CODE 1"
2840 END
2850 TG=WSPW*D*S                                   'Gross boundary stress
2860 TE=TG*(1-CF)*(NS/MANN)*(NS/MANN)              'Erosionally effective stress;
Handbook equation 1.13
2870 TV=TG-TE                                      'Vegetal stress
2880 IF FLAG(1)=0 THEN 2920                        'Governing stress identifier
2890 ERP=(TV-TVA)/TVA                              'Relative deviation of computed
stress from allowable; vegetal stress governing
2900 IF ABS(ERP)<.001 THEN 3200                    'Stress convergence check
2910 GOTO 2940
2920 ERP=(TE-TA)/TA                                'Relative deviation of computed
stress from allowable; erosionally effective stress
2930 IF ABS(ERP)<.001 THEN 3190                    'Stress convergence check
2940 JD2=JD2+1                                     'Iteration loop counter
2950 IF SGN(ERP)*ISAL<0 THEN 3140              'Geometric limiting condition check
2960 ISAL=0
2970 ' WIDTH ADJUSTMENT
2980 IF JD2>1 THEN 3090
2990 WADJ=.1*SGN(ERP)*W                          'Width adjustment
3000 WP=W
3010 TEP=TE
3020 TVP=TV
3030 IF ABS(WADJ)<.3*W THEN 3060
3040 WADJ=.7*WADJ
3050 GOTO 3030
3060 W=W+WADJ
3070 IF JD2>40 THEN 3160
3080 ON CTYP GOTO 2480,2560,2620
```

```
3090 IF FLAG(1)=0 THEN 3120
3100 WADJ=(W-WP)*(TVA-TV)/(TV-TVP)
3110 GOTO 3000
3120 WADJ=(W-WP)*(TA-TE)/(TE-TEP)
3130 GOTO 3000
3140 FLAG(2)=1                          'Stability applicability flag
3150 GOTO 3190                          'Re-compute conditions with adjusted width
3160 PRINT "       CONVERGENCE FAILURE; STABILITY       "
3170 END
3180 GOTO 3740
3190 IF TV>TVA THEN 3340                'Vegetal stress check
3200 IF CTYP=3 THEN 3230
3210 TWD=B+2*Z*D                        'Channel width at water surface
3220 GOTO 3250
3230 IF AA=0 THEN AA=1/(4*Z*Z*D)
3240 TWD=2*SQR(D/AA)
3250 GOSUB 4830
3260 ' FROUDE NUMBER LIMITS USED ARE SOMEWHAT ARBITRARY; JUDGMENT IS REQUIRED
3270 IF FR<.9 THEN 3290
3280 IF FR<1.1 THEN 3320
3290 IF FRC<.9 THEN 3310
3300 IF FRC<1.1 THEN 3320
3310 IF SGN(1-FR)=SGN(1-FRC) THEN 3600
3320 FLAG(3)=1                               'FROUDE no. stability check
3330 GOTO 3610
3340 FLAG(1)=1                          'Condition reset for vegetal stress control
3350 WP=W
3360 TVP=TV
3370 W=Q/(V*SQR(TVA/TV)*TVA/(WSPW*S))
3380 JD2=0
3390 JD1=0
3400 ON CTYP GOTO 2480,2560,2620
3410 ' BEGIN CHANNEL CAPACITY COMPUTATIONS  (Variable names are the same as in
previous section)
3420 JA=0                                    'Iteration loop counter
3430 A=Q/V
3440 GOSUB 5480
3450 GOSUB 5590
3460 R=A/P
3470 RV=V*R
3480 GOSUB 5330
3490 MANN=DVV
3500 GOSUB 5440
3510 VM=DV
3520 VADJ=2*(VM-V)/3
3530 IF ABS(VADJ/VM)<.001 THEN 3200
3540 V=V+VADJ
3550 JA=JA+1
3560 IF JA<30 THEN 3430
3570 PRINT " CONVERGENCE FAILURE; CAPACITY"
3580 END
3590 GOTO 3740
3600 IF V*R<.0025*CI^2.5 THEN FLAG(5)=1           'Check of n-VR curve limits
3610 IF V*R>36 THEN FLAG(5)=1
```

```
3620 IF CTYP=3 THEN 3700
3630 IF CTYP<>1 THEN 3740
3640 IF BMIN>=0 THEN 3740
3650 DOPT=SQR(A/(2*SQR(1+Z*Z)-Z))
3660 BOPT=A/DOPT-Z*DOPT                              'APPROXIMATE hydraulically
optimum trapezoidal channel bed width
3670 BMIN=BOPT
3680 IF B>=BMIN THEN 3740
3690 GOTO 2490
3700 Z=1/(2*SQR(AA*D))      'Parabolic channel bank slope      at water surface
3710 IF 1.01*Z>ZMIN THEN 3740
3720 EDPT=D
3730 GOTO 2650
3740 PRINT TAB(2)                                    'Parameter printout
3750 IF CIIC$="CAPACITY" THEN 3970
3760 PRINT "                              OUTPUT"
3770 PRINT
3780 PRINT "           GRASS-LINED ";CTYPE$;" CHANNEL"
3790 PRINT
3800 PRINT TAB(5);"SOLUTION FOR STABILITY";TAB(5);"(establishes geometric
control)"
3810 PRINT
3820 PRINT
3830 GOTO 4060
3840 PRINT TAB(5);SOIL$;" SOIL BOUNDARY"
3850 IF SLIN$="V" THEN 3880
3860 IF SLIN$="S" THEN 3940
3870 GOTO 3900
3880 PRINT TAB(7);"REFERENCE PERMISSIBLE VELOCITY =";VA;" ft/s"
3890 GOTO 3980
3900 IF ISL>10 THEN 3930
3910 PRINT TAB(7);"PLASTICITY INDEX =";IW
3920 IF EV<>0 THEN PRINT "       VOID RATIO        =";EV
3930 IF IW<10 THEN PRINT "       d75 PARTICLE DIAMETER =";D75;" inches"
3940 PRINT "         ALLOWABLE EFFECTIVE STRESS =";INT(10000*TA+.5)/10000;"
lb/sq.ft"
3950 PRINT "         SOIL GRAIN ROUGHNESS COEFFICIENT =";INT(10000*NS+.5)/10000
3960 GOTO 3980
3970 PRINT TAB(5);"SOLUTION FOR CAPACITY";TAB(5);"(establishes required flow
depth)"
3980 IF CIF$="SCS" THEN PRINT TAB(5);COVER$;" COVER FALLS IN SCS RETARDANCE CLASS
'";RC$;"'"
3990 PRINT
4000 IF CIF$<>"SCS" THEN PRINT TAB(5);COVER$;" VEGETAL COVER"
4010 IF CIF$<>"LD" THEN 4060
4020 PRINT "         STEM LENGTH = ";GH;" ft"
4030 PRINT "         STEM COUNT = ";SC;" stems/ft/ft"
4040 PRINT
4050 PRINT
4060 PRINT TAB(7);" CURVE     MANNING    AVERAGE    VOLUMETRIC";
4070 IF CIIC$="CAPACITY" THEN 4100
4080 PRINT "  COVER  ";
4090 IF SLIN$<>"V" THEN PRINT "    EFFECTIVE";
4100 PRINT " "
```

```
4110 PRINT TAB(6);"  INDEX     COEFFIC.  VELOCITY  DISCHARGE";
4120 IF CIIC$="CAPACITY" THEN 4150
4130 PRINT "   FACTOR ";
4140 IF SLIN$<>"V" THEN PRINT "    SOIL STRESS";
4150 PRINT
4160 PRINT "                             ft/s       cu.ft/s          ";
4170 IF CIIC$="CAPACITY" THEN 4190
4180 IF SLIN$<>"V" THEN PRINT "      lb/sq.ft";
4190 PRINT " "
4200 PRINT USING "    #####.##      #.###     ####.##     ####.##";CI,MANN,V,Q;
4210 IF CIIC$="CAPACITY" THEN 4240
4220 PRINT USING "      ###.##";CF;
4230 IF SLIN$<>"V" THEN PRINT USING "   ####.####";TE
4240 PRINT " "
4250 PRINT " "
4260 IF CTYP=1 THEN 4300
4270 IF CTYP=2 THEN 4310
4280 PRINT "        X-SECT.";
4290 GOTO 4310
4300 PRINT "        BOTTOM";
4310 PRINT "    TOP       FLOW      SIDE    X-SECT.    HYDRAULIC     BED"
4320 IF CTYP=1 THEN 4360
4330 IF CTYP=2 THEN 4370
4340 PRINT "        COEFF.";
4350 GOTO 4370
4360 PRINT "         WIDTH";
4370 PRINT "    WIDTH     DEPTH     SLOPE     AREA       RADIUS       SLOPE"
4380 IF CTYP=1 THEN 4420
4390 IF CTYP=2 THEN 4430
4400 PRINT "              ";
4410 GOTO 4430
4420 PRINT "           ft";
4430 PRINT "        ft        ft        z:1 .    sq.ft        ft          ft/ft"
4440 IF CTYP=1 THEN 4480
4450 IF CTYP=2 THEN 4490
4460 PRINT USING "   ###.#####";AA;
4470 GOTO 4490
4480 PRINT USING "   ######.#";B;
4490 PRINT USING "   #####.#    ####.##    ###.##   ####.#     ####.##
#####.###";TWD,D,Z,A,R,S
4500 PRINT
4510 ' FLAGGING OF UNUSUAL DESIGN CONDITIONS FOR ADDITIONAL CONSIDERATION
4520 IF FLAG(3) <> 1 THEN 4560
4530 PRINT "         FROUDE NUMBER = ",INT(100*FR+.5)/100
4540 PRINT
4550 PRINT "* A Froude number this close to 1 may result in water surface
instability."
4560 IF FLAG(5)=1 THEN PRINT "* WARNING, Reynolds No. outside primary solution
region for flow resistance",TAB(1)
4570 IF FLAG(2)<>1 THEN 4610
4580 IF FLAG(1)=1 THEN 4610
4590 PRINT "* The limiting value of ";LPARM$;" was found to control channel
dimensions"
4600 PRINT "  Stability is probably NOT the limiting factor in this case"
```

```
4610 IF FLAG(1)=1 THEN PRINT "* A computed vegetal stress of ";INT(100*TV)/100;"
lb/sq.ft controls channel dimensions"
4620 IF FLAG(4)=1 THEN PRINT "* The low value of the retardance curve index makes
the assumption";TAB(1);" of negligable 'form roughness' questionable'"
4630 IF PL=1 THEN 4720
4640 IF A$="Y" THEN 4710
4650 PRINT
4660 PRINT
4670 PRINT " IF YOU WANT A HARD COPY HIT Y , ANY OTHER KEY TO CONTINUE"
4680 A$=INKEY$ :IF A$ = "" THEN 4680
4690 IF A$="Y" THEN 4710
4700 GOTO 4730
4710 GOSUB 5710
4720 IF CIIC$="CAPACITY" THEN LPRINT CHR$(12)
4730 IF CIIC$="STABILITY" THEN 4760
4740 PRINT"                                    PROGRAM COMPLETE"
4750 END
4760 CIIC$="CAPACITY"
4770 CLS
4780 FOR II=1 TO 5: FLAG(II)=(0): NEXT II           'RESET OF SPECIAL CONDITION
FLAGS FOR CAPACITY CALCULATIONS
4790 PL=0
4800 ANSWER$=ANS$
4810 PRINT TAB(5)
4820 GOTO 1640
4830       ' COMPUTATION OF FROUDE NUMBER FOR A VEGETATED CHANNEL
4840 ' COMPUTATION OF UNIT DISCHARGE AND VELOCITY WITH SLOPE, DEPTH, AND VEGETAL
CURVE INDEX GIVEN
4850 RVL=.0025*CI^2.5
4860 RVU=36
4870 ADV=COE(1)*CI
4880 BDV=1+COE(2)*CI
4890 CDVA=-(LOG(1.4859)+LOG(S)/2-COE(4)-COE(3)*CI)
4900 CDV=CDVA-5*LOG(D)/3
4910 DISC=BDV*BDV-4*ADV*CDV
4920 IF DISC<0 THEN 5020
4930 QU=EXP((-BDV+SQR(DISC))/(2*ADV))               'Unit discharge based on 2-d
flow at depth D
4940 IF QU>RVU THEN 5030
4950 IF QU<RVL THEN 5030
4960 GOSUB 5090
4970 VCN=QU/D                      'Mean velocity based on 2-d flow at depth D
4980 FRC=VCN/SQR(GR*D/ALPC)        'Froude number based on 2-d flow at depth D
4990 ALP=ALPC*(VCN/V)^(3/4)        'Energy coefficient for the X-section
5000 FR=V/SQR(GR*A/TWD/ALP)        'Froude number for the X-section
5010 RETURN
5020 QU=RVL
5030 GOSUB 5330
5040 MNC=DVV
5050 GOSUB 5440
5060 VCN=DV
5070 QU=VCN*D
5080 GOTO 4960
5090 'COMPUTATION OF ENERGY COEFFICIENT UNDER WIDE CHANNEL(2-d flow)ASSUMPTION
```

```
5100 '         (SOLUTION OF HANDBOOK EQUATION 1.8)
5110 IF QU<RVL THEN 5290
5120 IF QU>RVU THEN 5310
5130 IF S<.0001 THEN 5310
5140 X01=LOG(QU/RVL)/LOG(RVU/RVL)
5150 XCO=ALCO(5,4)*LOG(S)
5160 FOR IA=1 TO 4
5170 XCO=XCO+ALCO(IA,4)*CI^(IA-1)
5180 NEXT IA
5190 ECO=0
5200 FOR JA=1 TO 3
5210 ECOJ=ALCO(5,JA)*LOG(S)
5220 FOR IA=1 TO 4
5230 ECOJ=ECOJ+ALCO(IA,JA)*CI^(IA-1)
5240 NEXT IA
5250 ECO=ECO+ECOJ*X01^(JA-1)
5260 NEXT JA
5270 ALPC=1+X01^XCO*EXP(ECO)
5280 RETURN
5290 ALPC=1
5300 RETURN
5310 ALPC=1.04
5320 RETURN
5330                                        ' n-VR Curves
5340 RVI=RV
5350 RVM=.0025*CI^2.5
5360 IF RVI>36 THEN RVI=36
5370 IF RVI<RVM THEN RVI=RVM
5380 DV=LOG(RVI)
5390 DVV=COE(1)*DV*DV+COE(2)*DV+COE(3)
5400 DV=CI*DVV+COE(4)
5410 DVV =EXP(DV)
5420 RETURN
5430                                                  'Manning's equation
5440 EX=2/3
5450 DV=AU/MANN*R^EX*SQR(S)
5460 RETURN
5470                                        'Flow depth from channel geometry
5480 ON CTYP GOTO 5490,5510,5530
5490 D=(-B+SQR(B*B+4*A*Z))/(2*Z)
5500 RETURN
5510 D=SQR(A/Z)
5520 RETURN
5530 IF AA<>0 THEN 5560
5540 D=SQR(3*A/(8*Z))
5550 RETURN
5560 D=(.75*A*SQR(AA))^(2/3)
5570 RETURN
5580                                   'Wetted perimeter from channel geometry
5590 ON CTYP GOTO 5600,5620,5640
5600 P=B+2*D*SQR(Z*Z+1)
5610 RETURN
5620 P=2*D*SQR(Z*Z+1)
5630 RETURN
```

```
5640 IF AA<>0 THEN 5670
5650 P=2*D*(SQR(Z*Z+1)+Z*Z*LOG(1/Z*(1+SQR(Z*Z+1))))
5660 RETURN
5670 P=SQR(D*D+D/(4*AA))+LOG((SQR(D)+SQR(D+1/(4*AA)))/SQR(1/(4*AA)))/(4*AA)
5680 P=2*P
5690 RETURN
5700 '
5710 IF CIIC$="CAPACITY" THEN 5930
5720 LPRINT "                              OUTPUT"
5730 LPRINT
5740 LPRINT "            GRASS-LINED ";CTYPE$;" CHANNEL"
5750 LPRINT
5760 LPRINT" -----------------------------------------------------------------------
--- "
5770 LPRINT TAB(5);"SOLUTION FOR STABILITY";TAB(5);"(establishes geometric
control)"
5780 LPRINT
5790 LPRINT
5800 LPRINT TAB(5);SOIL$;" SOIL BOUNDARY"
5810 IF SLIN$="V" THEN 5840
5820 IF SLIN$="S" THEN 5900
5830 GOTO 5860
5840 LPRINT TAB(7);"REFERENCE PERMISSIBLE VELOCITY =";VA;" ft/s"
5850 GOTO 5940
5860 IF ISL>10 THEN 5890
5870 LPRINT TAB(7);"PLASTICITY INDEX =";IW
5880 IF EV<>0 THEN LPRINT "         VOID RATIO        =";EV
5890 IF IW<10 THEN LPRINT "         d75 PARTICLE DIAMETER =";D75;" inches"
5900 LPRINT "         ALLOWABLE EFFECTIVE STRESS =";INT(10000*TA+.5)/10000;"
lb/sq.ft"
5910 LPRINT "         SOIL GRAIN ROUGHNESS COEFFICIENT =";INT(10000*NS+.5)/10000
5920 GOTO 5940
5930 LPRINT TAB(5);"SOLUTION FOR CAPACITY";TAB(5);"(establishes required flow
depth)"
5940 IF CIF$="SCS" THEN LPRINT TAB(5);COVER$;" COVER FALLS IN SCS RETARDANCE CLASS
'";RC$;"'"
5950 LPRINT
5960 IF CIF$<>"SCS" THEN LPRINT TAB(5);COVER$;" VEGETAL COVER"
5970 IF CIF$<>"LD" THEN 6020
5980 LPRINT "         STEM LENGTH = ";GH;" ft"
5990 LPRINT "         STEM COUNT = ";SC;" stems/ft/ft"
6000 LPRINT
6010 LPRINT
6020 LPRINT TAB(7);" CURVE     MANNING   AVERAGE   VOLUMETRIC";
6030 IF CIIC$="CAPACITY" THEN 6060
6040 LPRINT "  COVER  ";
6050 IF SLIN$<>"V" THEN LPRINT "    EFFECTIVE";
6060 LPRINT " "
6070 LPRINT TAB(6);"  INDEX     COEFFIC.  VELOCITY  DISCHARGE";
6080 IF CIIC$="CAPACITY" THEN 6110
6090 LPRINT "   FACTOR ";
6100 IF SLIN$<>"V" THEN LPRINT "    SOIL STRESS";
6110 LPRINT
6120 LPRINT "                              ft/s      cu.ft/s          ";
```

```
6130 IF CIIC$="CAPACITY" THEN 6150
6140 IF SLIN$<>"V" THEN LPRINT "      lb/sq.ft";
6150 LPRINT
6160 LPRINT USING "    #####.##     #.###     ####.##     ####.##";CI,MANN,V,Q;
6170 IF CIIC$="CAPACITY" THEN 6200
6180 LPRINT USING "     ###.##";CF;
6190 IF SLIN$<>"V" THEN LPRINT USING "   ####.####";TE
6200 LPRINT
6210 LPRINT
6220 IF CTYP=1 THEN 6260
6230 IF CTYP=2 THEN 6270
6240 LPRINT "      X-SECT.";
6250 GOTO 6270
6260 LPRINT "      BOTTOM";
6270 LPRINT "   TOP      FLOW     SIDE   X-SECT.   HYDRAULIC     BED"
6280 IF CTYP=1 THEN 6320
6290 IF CTYP=2 THEN 6330
6300 LPRINT "      COEFF.";
6310 GOTO 6330
6320 LPRINT "       WIDTH";
6330 LPRINT "   WIDTH    DEPTH    SLOPE    AREA      RADIUS      SLOPE"
6340 IF CTYP=1 THEN 6380
6350 IF CTYP=2 THEN 6390
6360 LPRINT "          ";
6370 GOTO 6390
6380 LPRINT "         ft";
6390 LPRINT "      ft       ft      z:1      sq.ft       ft         ft/ft"
6400 IF CTYP=1 THEN 6440
6410 IF CTYP=2 THEN 6450
6420 LPRINT USING "   ###.#####";AA;
6430 GOTO 6450
6440 LPRINT USING "   ######.# ";B;
6450 LPRINT USING "  #####.#    ####.##  ###.##    ####.#     ####.##
#####.###";TWD,D,Z,A,R,S
6460 LPRINT "  "
6470 ' FLAGGING OF UNUSUAL DESIGN CONDITIONS FOR ADDITIONAL CONSIDERATION
6480 IF FLAG(3) = 0 THEN 6520
6490 LPRINT "       FROUDE NUMBER = ",INT(100*FR+.5)/100
6500 LPRINT
6510 LPRINT "* A Froude number this close to 1 may result in water surface
instability."
6520 IF FLAG(5)=1 THEN LPRINT "* WARNING, Reynolds no. outside primary solution
region for flow resistance",TAB(1)
6530 IF FLAG(2)<>1 THEN 6570
6540 IF FLAG(1)=1 THEN 6570
6550 LPRINT "* The limiting value of ";LPARM$;" was found to control channel
dimensions"
6560 LPRINT "  Stability is probably NOT the limiting factor in this case"
6570 IF FLAG(1)=1 THEN LPRINT "* A computed vegetal stress of ";INT(100*TV)/100;"
lb/sq.ft controls channel dimensions"
6580 IF FLAG(4)=1 THEN LPRINT "* The low value of the retardance curve index makes
the assumption";TAB(1);"  of negligable 'form roughness' questionable'"
6590 LPRINT
6600 LPRINT
6610 LPRINT" ------------------------------------------------------------------
--- "
6620 IF PL=1 THEN 4720
6630 RETURN
```

OUTPUT

GRASS-LINED TRAPEZOIDAL CHANNEL

SOLUTION FOR STABILITY
(establishes geometric control)

CL SOIL BOUNDARY
PLASTICITY INDEX = 15
VOID RATIO = .9
ALLOWABLE EFFECTIVE STRESS = .047 lb/sq.ft
SOIL GRAIN ROUGHNESS COEFFICIENT = .0156

MIXED GRASS VEGETAL COVER
STEM LENGTH = .33 ft
STEM COUNT = 270 stems/ft/ft

CURVE INDEX	MANNING COEFFIC.	AVERAGE VELOCITY ft/s	VOLUMETRIC DISCHARGE cu.ft/s	COVER FACTOR	EFFECTIVE SOIL STRESS lb/sq.ft
4.39	0.036	4.99	500.00	0.75	0.0470

BOTTOM WIDTH ft	TOP WIDTH ft	FLOW DEPTH ft	SIDE SLOPE z:1	X-SECT. AREA sq.ft	HYDRAULIC RADIUS ft	BED SLOPE ft/ft
121.6	126.4	0.81	3.00	100.3	0.79	0.020

SOLUTION FOR CAPACITY
(establishes required flow depth)

MIXED GRASS VEGETAL COVER
STEM LENGTH = 2 ft
STEM COUNT = 330 stems/ft/ft

CURVE INDEX	MANNING COEFFIC.	AVERAGE VELOCITY ft/s	VOLUMETRIC DISCHARGE cu.ft/s
8.28	0.077	3.15	500.00

BOTTOM WIDTH ft	TOP WIDTH ft	FLOW DEPTH ft	SIDE SLOPE z:1	X-SECT. AREA sq.ft	HYDRAULIC RADIUS ft	BED SLOPE ft/ft
121.6	129.2	1.27	3.00	159.0	1.23	0.020

OUTPUT

GRASS-LINED PARABOLIC CHANNEL

SOLUTION FOR STABILITY
(establishes geometric control)

CL SOIL BOUNDARY
PLASTICITY INDEX = 15
VOID RATIO = .9
ALLOWABLE EFFECTIVE STRESS = .047 lb/sq.ft
SOIL GRAIN ROUGHNESS COEFFICIENT = .0156

BERMUDAGRASS VEGETAL COVER
STEM LENGTH = .25 ft
STEM COUNT = 670 stems/ft/ft

CURVE INDEX	MANNING COEFFIC.	AVERAGE VELOCITY ft/s	VOLUMETRIC DISCHARGE cu.ft/s	COVER FACTOR	EFFECTIVE SOIL STRESS lb/sq.ft
4.66	0.033	6.86	500.00	0.90	0.0470

X-SECT. COEFF.	TOP WIDTH ft	FLOW DEPTH ft	SIDE SLOPE z:1	X-SECT. AREA sq.ft	HYDRAULIC RADIUS ft	BED SLOPE ft/ft
0.00151	66.2	1.65	10.02	72.9	1.10	0.020

SOLUTION FOR CAPACITY
(establishes required flow depth)

BERMUDAGRASS VEGETAL COVER
STEM LENGTH = .25 ft
STEM COUNT = 830 stems/ft/ft

CURVE INDEX	MANNING COEFFIC.	AVERAGE VELOCITY ft/s	VOLUMETRIC DISCHARGE cu.ft/s
4.83	0.034	6.74	500.00

X-SECT. COEFF.	TOP WIDTH ft	FLOW DEPTH ft	SIDE SLOPE z:1	X-SECT. AREA sq.ft	HYDRAULIC RADIUS ft	BED SLOPE ft/ft
0.00151	66.6	1.67	9.95	74.2	1.11	0.020

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