HYDRAULIC DESIGN OF A CHANNEL ADAPTED TO USE AS A SALMON SPAWNING FACILITY

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Summary

Basic requirements of a spawning channel are (1) a bed of medium and coarse gravel and (2) a velocity of 2.0 feet per second at a point 0.3 foot above the bed, according to biologists of the Fish and Wildlife Service. A series of relationships is assembled in the following pages to permit expression of these criteria in terms of the geometry and hydraulic properties of a channel.

The presence of a gravel bed is reflected in terms of a Manning's "n" of 0.025 for an undisturbed bed to "n" of 0.030 for a bed disturbed by redd building. The effect of different roughnesses for the bed (gravel) and the side slopes (concrete) is handled through an equivalent "n" function.

The bed velocity criteria are expressed in terms of bulk or sectional properties through the semilogarithmic function for velocity profile in the vicinity of a boundary in terms of local shearing stress and rugosity.

The integrated impact of biological and hydraulic criteria is demonstrated for several cross sections and discharges by means of graphs which juxtapose curves of conveyance and bottom (near bed) velocity criteria. At intersections of related curves are found

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parametric values of depth and slope which simultaneously meet conveyance and bed velocity requirements.

The basic requirements of a channel for spawning salmon, whether it be a single-purpose spawning channel or a dual-purpose irrigation-spawning channel, have been stated in terms of (1) the physical condition of the bed, size, and gradation of gravel, and (2) the velocity field in the vicinity of the bed. Although seemingly separate the two parameters are probably derivable from, and related to, the general requirement that salmon eggs deposited in the bed material of a channel require a minimum oxygen content in the ambient waters and protection from dislodgment during the incubation period. The physical character of the bed in terms of the gravel size and gradation together with the specifications of velocity near the bed are only two of the explicit environmental factors which spawning salmon can recognize and identify as requirements for their needs. Other factors include (1) water temperature, (2) the presence or absence of fine sediment which could decrease permeability and oxygenation rate, and (3) the presence of local undulations of the bed profile which favorably modify average conditions (riffles or redds).

It has been determined by measurements in natural channel and by experience with artificial spawning channels that bed gravels should be in the size range from 1 to 6 inches in diameter, and that velocities at a point 0.3 foot above the bed should be in the range

1.5 to 2.5 feet per second. The hydraulic properties of a channel meeting these conditions may be established by considering the related combinations of boundary shear, depth, and slope.

Conventional formula used in designing channels, such as Manning's formula, by which the geometric properties of a channel, including invert slope, are established to provide the required conveyance are not suitable. They relate to mean sectional velocity and do not provide the information on near-bed velocities required for the design of spawning channels.

The semilogarithmic relation between boundary shear and velocity profile developed from studies of closed conduit flow and adapted to open channel conditions offer a means of identifying local conditions. A convenient form of the semilogarithmic relation, for fully developed turbulent flow, is one containing the roughness factor "k," viz.

$$v_y = 5.75\sqrt{\frac{\tau_o}{\rho}}\log\frac{30y}{k} \qquad (1)$$

where y = distance from boundary in feet

τ_o = local boundary shear in pound per square foot

v_y = velocity at distance y from boundary in feet

k = roughness (equivalent sand grain diameter in feet)

ρ = mass density slugs per cubic foot

If "k" is known or assigned, Equation (1) may be used to compute velocities near the bed for various values of boundary shear "τ_o." Since much of the available data on channel roughness is in the form of the coefficient "n" in Manning's or Kutter's equations, a relationship between "n" and "k" is needed. The Strickler formula provides such a relationship in the form:

$$n = 0.0342^{1/6}$$

This equation was developed from data on natural streams and is suitable for use in such streams.[1/] (Strickler used the median sieve size of the bed material for roughness height.) For use in artifical channels within a limited depth range a more appropriate coefficient for the Strickler equation may be developed from Equation (1) and the Manning equation. Equating the average velocity obtained by each equation, substituting depth for hydraulic radius (wide shallow channels) and setting $y = 0.4d$.

$$\overline{V} = \frac{1.49}{n} d^{2/3} s^{1/2} = 5.75 \sqrt{gds} \log\left(\frac{12d}{k}\right)$$

from which

$$\frac{\left(\frac{d}{k}\right)^{1/6}}{21.9 \log\left(\frac{12d}{k}\right)} k^{1/6} \qquad (2)$$

Over the range of depths from 2.0 to 8.0 feet and "n" from 0.020 to 0.030 the relationship between "n" and "k" may be approximated as follows:

$$n = 0.032\ k^{1/6} \qquad (3)$$

[1/] See list of references at end of text.

With the value of "k" established, the velocity profile is a function only of the local boundary shear, "τ_o." The value of average boundary shear in a canal may be related to the general conditions of flow by the expression;

$$\bar{\tau}_o \text{ (average)} = \gamma R s$$

where $\bar{\tau}_o$ (average) = average shear stress for section

R = hydraulic radius in feet

s = slope of energy line

γ = specific weight of water

For purposes of simplifcation the problem will be treated as a two-dimensional case by assuming that the expression for local shear (γds) applies over the entire bed. This assumption approximates conditions in wide shallow channels and leads to relationships which are useful in planning studies but an adjustment is required for narrower and deeper channels. The adjustment will be made subsequently by a method based on work done by the Bureau of Reclamation in stable channel design which has been summarized by Chow.[1/]

Rewriting Equation (1) in terms of γds yields the following:

$$v_y = 5.75 \sqrt{g} \sqrt{ds} \log\left(\frac{30y}{k}\right) \quad \text{(1a)}$$

In this form the equation is useful for relating the fishery requirements to the geometrical elements of a channel, including gravel bed roughness which is implicit in the factor **k**.

A basic requirement for a spawning channel is a thick layer of gravel of large size on the bed. Such a condition which occurs naturally in the form of riffles is accomplished in artificial channels by covering the bed with a layer of washed gravels, 2 to 3 feet thick, in the size range from 1 to 6 inches in diameter. Based on measurements in natural channels and experience with artificial spawning facilities a desirable gradation of gravel is one with 50 percent or less between 1 and 3 inches and 40 percent or more (up to 70 percent) between 3 and 6 inches.

The boundary resistance of gravel beds of the size and gradation suitable for spawning was determined in a series of flume studies for the McNary spawning channel.[2/] Results indicated an "n" value of 0.025 at velocities of 1 to 1-1/2 feet per second and depths of 1 to 1-1/2 feet. The value of "k" corresponding to an "n" of 0.025 and a depth of 2.0 feet from Equation (2) is found to be 0.20 foot. The more approximate value from Equation (3) would be 0.22 foot. The round value of 0.20 foot for "k" corresponding to an "n" of 0.025 will be used.

A further consideration of boundary resistance must include disturbances of the bed due to the redd building involved in the spawning activity.

The longitudinal profile of an average redd was assumed to be an undulation consisting of a depression, up to 12 inches deep and 11 feet long, followed by a hump 9 inches high and 6 feet long.[3/] The effect of these disturbances on boundary resistance was approximated by superimposing the form drag of the redds on the boundary shear of an undisturbed gravel bed. The procedure which is described in the appendix results in an increase in Manning's "n." The apparent or overall value for a roughened bed (n_a) in the depth range from 5.0 to 8.0 feet varies from 0.028 to 0.029. Because of the many assumptions involved in the procedure a conservative value of $n_a = 0.030$ will be used for a gravel bed disturbed by redd building.

The problem of designing for the two bed conditions, before and after redd building, was resolved as follows. Geometrical properties of the channel, including invert slope, were selected to meet fishery requirements on the basis of an undisturbed bed. It was reasoned that, although the presence of redds would decrease the near-bed velocities on the average, the local velocities in the vicinity of the redds would be high enough to meet spawning requirements. Observations of spawning salmon indicate that they are, in fact, attracted to the vicinity of existing redds. The average near-bed velocity for disturbed bed conditions was computed and is shown as a matter of interest and background. The effect of bed disturbance on conveyance is reflected through the use of appropriate values of "n," as will be shown subsequently.

The channel characteristics for wide, shallow channels may now be related to the spawning requirements using the foregoing relationships which are recapitulated for easy reference as follows:

$$v_y = 5.75\sqrt{\frac{\tau_o}{\rho}}\ \log\frac{30y}{k} = 5.75\sqrt{gds}\ \log\frac{30y}{k} \qquad (1)$$

$$n = 0.032\ k^{1/6} \qquad (3)$$

The various combinations of depth and slope for a given roughness which meet the velocity criterion may be developed from Equations (1) and (3).

Setting "k" = 0.20 foot, equivalent to an "n" of 0.025 and specifying that the velocity at a point 0.3 foot above the bed be equal to 2.0 feet per second the following relationship ensues:

$$v_{0.3} = 5.75\ \sqrt{g}\ \sqrt{ds}\ \ \log\frac{30 \times 0.3}{0.20} = 53.8\ \sqrt{ds}$$

For the value of $v_{0.3} \geqq 2.0$ feet per second

$$53.8\sqrt{ds} \geqq 2.0$$

or

$$\sqrt{ds} \geqq \frac{2.0}{53.8} \geqq 0.0372$$

and

$$ds \geqq 0.00138 \qquad (4)$$

A plot of this function is shown in Figure 1. Points to the right and above the curve correspond to velocities greater than 2.0 feet per second.

A similar relationship may be developed for a bed roughened by redd construction to an "n" value of 0.030.

The related value of "k" is:

$$k = \left(\frac{0.030}{0.032}\right)^6 = 0.67$$

$$v_{0.3} = 5.75\ \sqrt{g}\ \sqrt{ds}\ \log\frac{30 \times 0.3}{0.67} = 36.7\ \sqrt{ds}$$

and

$$\sqrt{ds} \geqq \frac{2.0}{36.7} \geqq 0.0545$$

$$ds \geqq 0.00297 \qquad (5)$$

This function is also shown in Figure 1. It will be noted that the value of the equivalent roughness "k" is 0.67 feet which exceeds the maximum size of bed gravel.

The discharges corresponding to the various combination of depth (d) and slope (s) which meet the velocity criterion according to Equations (4) and (5) may be developed from semilogarithmic function for wide shallow channels. It is assumed that the average velocity occurs at a distance of 0.6 depth (0.6d) from the water surface or 0.4d from the bottom. With a value of "k" = 0.20 the relation of Equation (4) applies.

$$ds \geqq 0.00138$$

Then $\overline{V}$ (average velocity) $= 5.75\sqrt{g} \times \sqrt{0.00138}\ \log\frac{30 \times 0.4d}{0.20}$

$$\overline{V} = 1.21 \log 60d \qquad (6)$$

and q (discharge per foot of width) = $\bar{V}d$

Then, $$\bar{V}d = 1.21\ d \log 60d \qquad (7)$$

The more useful relation between q and s can be developed by substituting

$$d = \frac{0.00138}{s}$$

$$q = 1.21 \times \frac{0.00138}{s} \log \left(\frac{60 \times 0.00138}{s} \right)$$

simplified to

$$q = \frac{0.00167}{s} \log \frac{0.083}{s} \qquad (8)$$

The relation of "q" to "s" is plotted in Figure 2.

When "k" is 0.67 and $ds \geqq 0.00297$ (Equation (5))

$$\bar{V} = 5.75 \sqrt{g} \times \sqrt{0.00297} \log \frac{30 \times 0.4d}{0.67}$$

$$\bar{V} = 1.78 \log 17.9d \qquad (9)$$

The unit discharge becomes

$$q = 1.78 \log 17.9d \qquad (10)$$

which in terms of "q" and "s," since

$$ds \geqq 0.00297 \quad \text{or} \quad d = \frac{0.00297}{s}$$

$$q = \frac{1.78 \times 0.00297}{s} \log \left[\frac{17.9 \times 0.00297}{s} \right]$$

$$q = \frac{0.00529}{s} \log \left[\frac{0.053}{s} \right] \tag{11}$$

Equation (11) is plotted on Figure 2.

For a wide shallow channel the unit discharge required to produce the required spawning velocity at any given slope may be selected from the curves of Figure 2. For a given unit discharge the related slope may be picked off. The corresponding depth of flow for any combination on Figure 2 may be obtained from the appropriate curve of Figure 1.

For narrower and deeper channels, the simplifying assumption that $R = d$ does not apply. When the bed to depth ratio (b/d) exceeds 20, the depth exceeds the hydraulic radius by 10 percent. In such channels the depth-slope relations of Equations (4) and (5) may be adapted from a knowledge of the distribution of boundary shear. For channel with a b/d ratio of 2 the local shear at the centerline of a trapezoidal channel is $0.90\gamma ds$ and diminishes to about $0.75\gamma ds$ at the sides. For a b/d ratio of 4, the corresponding values are $0.97\gamma ds$ and $0.80\gamma ds$.[1/] The local shear decreases slowly from the centerline out and an average of 95 percent of the centerline value is applicable over 80 percent of the bed. Average values of $0.85\gamma ds$ for $b/d = 2$ and $0.92\gamma ds$ for $b/d = 4$, will be used.

For a base width to depth ratio $(b/d) = 2.0$ let average bed shear = 0.850γ ds. Then, to satisy the bottom velocity criterion,

$$v_{0.3} = 5.75\sqrt{g}\sqrt{0.85 \text{ ds}} \log \frac{30 \times 0.3}{0.20}$$

and

$$\text{ds} \geq \frac{0.00138}{0.85} = 0.00162 \qquad (4a)$$

For a b/d ratio of 4.0 average bed shear = 0.92γ ds and,

$$v_{0.3} = 5.75\sqrt{g}\sqrt{0.92 \text{ ds}} \log \frac{30 \times 0.3}{0.20}$$

and

$$\text{ds} = \frac{0.00138}{0.92} = 0.0015 \qquad (4b)$$

In other words the product of $d \times s$ should be increased by the reciprocal of the coefficient of average bed shear for trapezoidal channel. For a roughened channel with b/d ratio of 4.0,

$$\text{ds} = \frac{0.00297}{0.92} = 0.00323$$

With such a modification the related values of depth and slope can be selected to produce the required bed velocity.

The discharges corresponding to paired values of depth and slope can be found by means of the Manning formula,

$$Q = \frac{1.49}{n_e} A R^{2/3} s^{1/2}$$

where n_e is the equivalent value of "n" for different roughness of the bed and side slopes which may prevail in a spawning channel.

The equivalent "n" for a channel section of composite roughness may be determined by any of several methods. A convenient one that is used frequently is based on the assumption that the average sectional velocity applies to all segments of the section.[1/]

The resulting relationship is:

$$n_e = \left[\frac{P_b \, n_b^{1.5} + P_w \, n_w^{1.5}}{P_b + P_w} \right]^{2/3} \qquad (12)$$

where n_e = equivalent value for section

n_b = bed roughness

P_b = wetted perimeter of bed

n_w = wall roughness

P_w = wetted perimeter of walls

For sections with side slopes of 1-1/2 to 1 and a base to depth ratio (b/d), the following generalized relation applies:

$$n_e = \left[\frac{b/d \, n_b^{1.5} + 3.6 \, n_w^{1.5}}{3.6 + b/d} \right]^{2/3} \qquad (13)$$

With a b/d ratio of 2.0 the value of equivalent n_e for various values of bed and wall roughness would be as follows for a gravel bed and concrete side slopes (n_w = 0.015 in large canals).

When $n_b = 0.020$ and $n_w = 0.015$, $n_e = 0.017$

When $n_b = 0.025$ and $n_w = 0.015$, $n_e = 0.019$

When $n_b = 0.030$ and $n_w = 0.015$, $n_e = 0.021$

As the b/d ratio increases, the value of equivalent "n" (n_e) approaches the value of n_b. For example, when $b/d = 5.0$, $n_b = 0.020$ and $n_w = 0.015$, $n_e = 0.0182$.

For $n_b = 0.025$ and $n_w = 0.015$, $n_e = 0.021$.

Other values are shown in Figure 5.

Since much of the design work on spawning channels has been, and probably will be, done in terms of average velocity it would be useful to have a relationship between average velocity and the velocity at 0.3 foot from the bottom. If each velocity is expressed in terms of Equation (1a) there results:

$$v_{0.3} = 5.75\sqrt{gds}\ \log \frac{30 \times 0.3}{k}$$

$$\overline{V} = v_{0.4d} = 5.75\sqrt{gds}\ \log \frac{30 \times 0.4d}{k}$$

Subtracting one from the other,

$$\overline{V} - v_{0.3} = 5.75\sqrt{gds}\ \log \frac{0.4d}{0.3}$$

If this expression is divided by the expression for $\overline{V}$ there results:

$$\frac{\overline{V} - v_{0.3}}{\overline{V}} = 1 - \frac{v_{0.3}}{\overline{V}} = \frac{\log\left(\frac{0.4d}{0.3}\right)}{\log\left(\frac{30 \times 0.4d}{k}\right)}$$

Assume a value of $k = 0.20$ foot, then

$$\frac{v_{0.3}}{\overline{V}} = 1 - \frac{\log 1.33d}{\log 60d}$$

Values of the velocity ratio for various values of depth are tabulated below. Also shown are the values of average velocity ($\overline{V}$) required to produce a near-bed velocity of 2.0 feet per second ($v_{0.3} = 2.0$).

d (ft)	$\frac{v_{0.3}}{\overline{V}}$	$\frac{\overline{V}}{v_{0.3}}$	$\overline{V}$ ($v_{0.3}$ = 2.0 ft/sec)
1.0	0.931	1.08	2.15
2.0	0.796	1.26	2.51
3.0	0.733	1.37	2.73
4.0	0.695	1.44	2.88
6.0	0.647	1.55	3.09
8.0	0.618	1.62	3.24
10.0	0.595	1.68	3.41
12.0	0.578	1.75	3.46

It is noted that for small depths, 1.0 to 2.0 feet, the average velocity exceeds the bed velocity by only 10 to 20 percent. This explains why the design of many of the existing artificial spawning channels could be acceptably based on average velocity rather than near-bed velocity. However, at depths over 5.0 feet the ratio of average to bed velocity exceeds 50 percent and design should be based near-bed velocity.

Example of Use of Material

Assume that a flow of 2,000 cubic feet per second and a slope in the amount, $s = 0.00015$ are available and that the roughness of bed is $n_b = 0.025$, and of the sides, $n_w = 0.015$. From Equation (4), $ds \geq 0.00138$, the minimum depth of flow at the given slope and bed roughness which will meet the bed velocity criterion is 9.2 feet as a first approximation. If it is assumed that the base width is about 50 feet, the b/d ratio is about 5.0 and Equation (4b) should be used to refine the value of depth. From Equation (4b) ($ds = 0.0015$) the depth is found to be $d = 10.0$ feet.

For a b/d ratio of 5.0 the equivalent "n_e" for a channel with $n_b = 0.025$ and $n_w = 0.015$ is $n_e = 0.021$.

From Manning's equation with Q, n, d, and s known, any of the available handbooks can be used to find that for

$$\frac{Qn_e}{d^{8/3}\ s^{1/2}} = \frac{2,200 \times 0.021}{(10)^{8/3} \times 0.01225} = 8.1$$

$$d/b = 0.193 \quad \text{or} \quad b = \frac{10}{0.193} = 52 \text{ feet}$$

If it is desired to fix the base width at less than 52 feet, say 50.0 feet, a slightly smaller slope or some combination of smaller slope and larger depth could have been used.

In cases where the cross section of a canal is fixed by other criteria the various possible combinations of Q, slope and depth may be found conveniently by means of the conveyance concept as follows:

Assume a cross section with $b = 50.0$ feet; side slopes = 1-1/2 to 1; and $n_e = 0.021$.

The Manning equation may be written:

$$Q = \left(\frac{1.49}{n} A R^{2/3} \right) s^{1/2} = K s^{1/2} \qquad (14)$$

where K (conveyance) $= \frac{149}{n} A R^{2/3}$.

The values of K for various depths are plotted on Figure 4. The slope required to convey a given discharge at a given slope may be determined from a tabulation or the graph as follows:

Let $Q = 2{,}200$ cubic feet per second and $d = 10.0$ feet. From Figure 3 $K = 177.5 \times 10^3$ and from Equation (14)

$$s = \left(\frac{Q}{K} \right)^2 = \left(\frac{2{,}200}{177.5 \times 10^3} \right)^2 = 0.000154$$

The bottom velocity criterion of Equations (4), (4a), or (4b) can be added to the graph if the flow is given to provide a graphical solution.

For a b/d ratio of 4 or 5, Equation (4b) is appropriate.

$$ds = 0.0015 \quad (4b)$$

and

$$\sqrt{s} = \frac{0.0387}{\sqrt{d}}$$

Substituting in Equation (14)

$$Q = \frac{K \times 0.0387}{\sqrt{d}}$$

or

$$K = \frac{Q}{0.0387} \sqrt{d}$$

Assume $Q = 2{,}200$ cubic feet per second. Then,

$$K = \frac{2{,}200}{0.0387} \sqrt{d} = 56.9 \times 10^3 \sqrt{d}$$

Values of K and d from this equation are plotted on Figure 3. The intersection of the conveyance curve and the velocity criterion curve in Figure 3 points to the value of depth required to meet both conditions.

At the intersection,

$$d = 10.1 \text{ feet}$$

and

$$s = \frac{0.0015}{10.1} = 0.000148$$

Conveyance curves for additional values of n_e, applicable to a disturbed bed, are also shown on Figure 3 along with an additional velocity criterion curve representing Equation (5) modified for a b/d ratio of 4.0 to $ds = \frac{0.00297}{0.92} = 0.00323$.

The same data, with a fixed Q = 2,200 cubic feet per second, can be represented on a plot of d vs s as shown in Figure 4. Equation (14) ($Q = K s^{1/2}$) with Q = 2,200 becomes

$$s = \left(\frac{Q}{K}\right)^2 = \left(\frac{2{,}200}{K}\right)^2 = f(d)$$

Tabulated values are as follows:

d	K(n = 0.021)	$s = \left(\frac{2{,}200}{K}\right)^2$
2	11.32×10^3	0.0376
4	35.5×10^3	0.00386
6	72.8×10^3	0.00092
8	120.0×10^3	0.000336
10	177.5×10^3	0.000154
12	245.5×10^3	0.000081

Also shown on Figure 4 are functions of d vs s for $n_e = 0.024$ and $n_e = 0.025$ and the curves of bottom velocity criteria for bed roughness values of k = 0.20 and 0.67. Values of d and s can be picked off from the intersections of related curves of conveyance and velocity criteria.

It has been assumed in the foregoing tabulations and in Figures 3 and 4 that n_e is a constant. In fact, n_e varies with the b/d ratio according to Equation (13) as shown in Figure 5. Average values of n_e over the range of depths from 8 to 12 feet with $n_w = 0.015$ may be taken from Figure 5 as follows:

for $n_b = 0.025$; $n_e = 0.021$

$n_b = 0.030$; $n_e = 0.025$

Returning to Figure 4, the curves may be used to develop the influence of roughness. For example, the intersection marked as (1) represents values of d and s which meet the velocity and conveyance requirements, for $n_e = 0.021$, $v_{0.3} = 2.0$ feet per second with a channel having a base width of 50.0 feet. The paired values are $d = 10.1$; $s = 0.00015$.

If the bed becomes roughened by redd building to the point that "n_b" = 0.030 and $n_e = 0.025$ intersection (2) is the solution. The depth must be increased, by about 1.0 foot, to 11.1 feet to convey 2,200 cubic feet per second at $s = 0.00015$. This solution is found by going vertically from intersection (1) along a vertical at $s = 0.000148$ to intersection with conveyance curve for $n_e = 0.025$. The bottom velocity at the new depth will be decreased to $v_{0.3} = 1.40$ feet per second from the relation

$$v_{0.3} = 36.7\sqrt{0.92\ ds}$$

The problem may involve, as it did in one case, designing a special reach of an irrigation conveyance canal as a salmon spawning channel. The range of discharge involved was from 1,000 to 2,200 cubic feet per second, with a dependable flow of 1,800 cubic feet per second. The spawning areas of a series of channels with base widths of 26, 50, and 100 feet were computed using the procedures outlined previously to determine a practical canal section giving the greatest spawning area for the extra head loss involved. The canal as projected for irrigation use only had a base width of 26 feet, side slopes of 1-1/2 to 1, and an invert slope of 0.00008. Composite curves of conveyance and bottom velocity criteria for the three sections are shown in Figure 6. The characteristics are summarized in the following tabulation for a channel length of 30,000 feet.

Base width feet	Undisturbed bed			Disturbed bed			Extra head loss feet	Spawning area (gross) ft x 10^{-6}	Ratio of spawning area to extra head ft x 10^{-5}
	depth feet	slope	$v_{0.3}$ ft/sec	depth feet	slope	$v_{0.3}$ ft/sec			
26	13.6	0.00012	2.0	14.2	0.00012	1.40	1.2	0.75	6.25
50	10.1	0.000148	2.0	10.9	0.000148	1.43	2.05	1.50	7.32
100	6.55	0.00021	2.0	7.22	0.00021	1.43	3.6	3.0	7.70

From the tabulation it is apparent that the ratio of spawning area to extra head loss increases with base width. It was deemed impractical to go beyond a base width of 100 feet, so it was adopted for further study.

To facilitate study and discussion of the consequences of various flows and bed conditions on fishery and conveyance criteria the set of curves shown in Figure 7 were developed. They apply to canal with a gravel base, 100 feet wide, and concrete sides on a slope of 1 on 1-1/2. Since the dependable flow at the time of spawning will be 1,800 cubic feet per second, the invert slope for undisturbed bed conditions was selected to produce a near-bed velocity of 2.0 feet per second. The corresponding point on the graph and designated as (1) indicates a normal flow depth of 5.6 feet at an invert slope of 0.00025. The normal depth at maximum flow of 2,200 cubic feet per second, obtained by following a vertical at a slope value of 0.00025 to its intersection with the curve designated as $Q = 2,200$ cubic feet per second, would be 6.25 feet.

The near-bed velocity may be obtained by interpolating between curves of constant value for $v_{0.3}$. These curves are obtained by inserting various values of $v_{0.3}$ in Equation (7b). At maximum flow the near-bed velocity would be 2.1 feet per second as shown by intersection marked. (2) Although a value of $v_{0.3} = 2.0$ feet per second was considered to be the optimum spawning condition, a range from 1.5 to 2.5 feet per second is acceptable for limited periods. The lower limit is exceeded for flows at normal depth as low as $Q = 1,000$ cubic feet per second for which $v_{0.3}$ is nearly 1.7 feet per second.

It has been assumed in the preceding analysis that the canal could be operated at normal depth for the range of flows considered. Let it be assumed that the canal will be operated in a checked condition, i.e., depths will exceed normal values, for flows less than 1,800 cubic feet per second. Consider a flow of 1,500 cubic feet per second checked to a depth at the downstream end of 5.6 feet. The corresponding near-bed velocity obtained from Figure 7 by following a constant depth line (horizontal) at $d = 5.6$ feet to intersect the constant "Q" line for $Q = 1{,}500$ cubic feet per second at (3) is $v_{0.3} = 1.65$ feet per second. For the lesser depths upstream in the canal corresponding to backwater computation the related near-bed velocities may be obtained in a similar manner. Such considerations will serve to define acceptable operating conditions and the related design criteria.

The effect of redd building on conveyance may be obtained by recomputing normal depth for an increase in "n" from 0.023 to 0.027 or to whatever value is selected for effective "n" with a roughened bed. The value of the increased depth for $n_e = 0.027$, shown as intersection (4) in Figure 8 is 6.8 feet or an increase of 0.55 foot (6.80-6.25). This increase is well within the freeboard usually provided for a canal of this size.

Thus, a rather complete picture of conditions relating to both fishery and conveyance functions may be developed.

References

1. "Open Channel Hydraulics," by Ven Te Chow, McGraw-Hill Book Company, 1959

2. "The Robertson Creek Spawning Channel," by K. C. Lucas, The Canadian Fishery Culturist, No. 27, August 1960

3. "Characteristics of Spawning Nests of Columbia River Salmon," by C. J. Burner, Fishery Bulletin of Fish and Wildlife Service

APPENDIX

In designing a spawning channel, particularly a dual use channel, it is necessary to consider the boundary resistance of the channel after it has been disturbed by the spawning activity of salmon in the form of redds. The effect of these disturbances on boundary resistance was approximated as follows. Assume that each redd produces a drag (F) in the amount:

$$F = \gamma \, C_d \, A \frac{v^2}{2g} \qquad (1)$$

where C_d = drag coefficient

A = projected area normal to the flow, square foot

The longitudinal profile of each redd was assumed to be an undulation consisting of a depression up to 12 inches deep and 11 feet long followed by a hump 9 inches high and 6 feet long. The average width of a redd was taken to be 6 feet. The effective height of the hump measured from a datum part way into the depression was taken as 1.0 foot with a width of 6.0 feet. The projected area would then be 6.0 square feet. With the further assumption that the drag coefficient, C_d = 0.1 applied to the average velocity, the drag becomes: $F = 0.1 \times 62.4 \times 6.0 \, v^2/2g$.

Observations of redd size and spacing,[3/] indicate that redds of average size cover an area of 6 square yards or 54 square feet and may occupy 25 percent of the available bed area.

For a spawning channel after redds have been constructed there would be an additional boundary drag over 25 percent of the area in the amount of:

$$\tau'_o = \frac{NF}{LW} \text{ in pounds per square foot} \qquad (2)$$

where τ'_o = incremental resistance expressed as a unit shear

N = number of redds

L = length of reach

W = average width of bed

The number of redds can be estimated from the assumptions previously stated:

$$N = \frac{L \times W}{4 \times 54} \qquad (3)$$

where $\tau'_o = \dfrac{L \times W}{4 \times 54} \times \dfrac{0.1 \times 62.4 \times 6.0}{LW} \; \dfrac{\bar{V}^2}{2g}$

or $\tau'_o = 0.174 \dfrac{\bar{V}^2}{2g}$

The relative increase in the apparent value of "n" may be approximated by comparing the incremental shear with the shear for a flat bed. In the case of a flat gravel bed for which a value of $n = 0.025$ is appropriate the related shear can be derived from the Manning equation applied to a wide channel:

$$\bar{V} = \frac{1.49}{n} d^{2/3} \quad {}^{1/2} = \frac{1.49}{n} d^{1/6} \sqrt{ds}$$

then

$$ds = \left[\frac{n\bar{V}}{1.49}\, d^{1/6}\right]^2 = \left(\frac{n}{1.49}\right)^2 \frac{\bar{V}^2}{d^{1/3}}$$

This expression can be inserted in the general expression for shear:

$$\tau_o = \gamma\, ds$$

to obtain

$$\tau_o = \gamma\left(\frac{n}{1.49}\right)^2 \frac{\bar{V}^2}{d^{1/3}} = \gamma\left(\frac{n}{1.49}\right)^2 \frac{2g}{d^{1/3}}\ \frac{\bar{V}^2}{2g}$$

Setting $n = 0.025$

$$\tau_o = 62.4\left(\frac{0.025}{1.49}\right)^2 \times \frac{64.4}{d^{1/3}}\ \frac{\bar{V}^2}{2g} = \frac{1.13}{d^{1/3}}\ \frac{\bar{V}^2}{2g}$$

When depth is taken equal to 2.0 feet

$$\tau_o = \frac{1.13}{(2.0)^{1/3}}\ \frac{\bar{V}^2}{2g} = 0.895\ \frac{\bar{V}^2}{2g}$$

From the expression $\tau_o = \gamma\, ds$ we know that the energy slope, s, varies with boundary shear, τ_o, for a fixed depth.

From Manning's with the terms rearranged as follows:

$$n = \frac{149}{\bar{V}}\, d^{2/3}\ s^{1/2}$$

the apparent value of "n" varies with the square root of the energy slope for fixed values of velocity, v, and depth, d. Then, apparent value of "n" (n_a) varies as the square root of the boundary shear.

Thus

$$\frac{n_a}{n} = \left(\frac{\tau_o + \tau_o'}{\tau_o}\right)^{1/2}$$

Using the expression for τ_o' derived previously i.e., $\tau_o' = 0.174\ \bar{V}^2/2g$ and the value of τ_o for depth = 2.0 feet, $\tau_o = 0.895\ \bar{V}^2/2g$

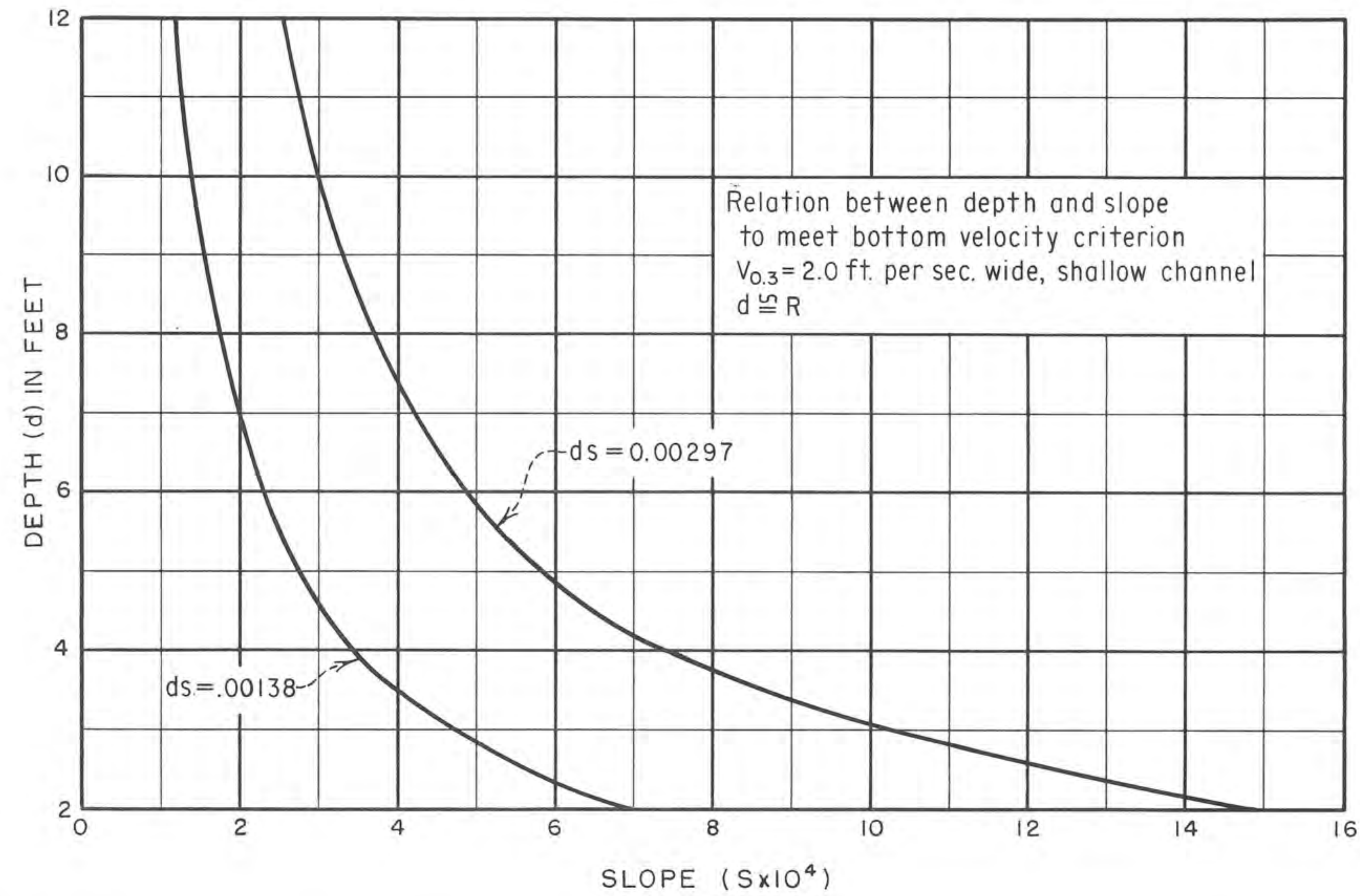
$$\frac{n_a}{n} = \left(\frac{0.895 + 0.174}{0.895}\right)^{1/2} = 1.09$$

then $n_a = 1.09\ n = 1.09 \times 0.025 = 0.0273$

When n_a is the apparent, or overall, value of Manning's "n" with the localized drag of the redds included. Values of apparent "n_a" for a depth range from 5.0 to 8.0 feet are 0.028 and 0.029, respectively. Because of the many assumptions involved in the foregoing development a conservative value of $n_a = 0.030$ will be used for a gravel bed disturbed by redd building.

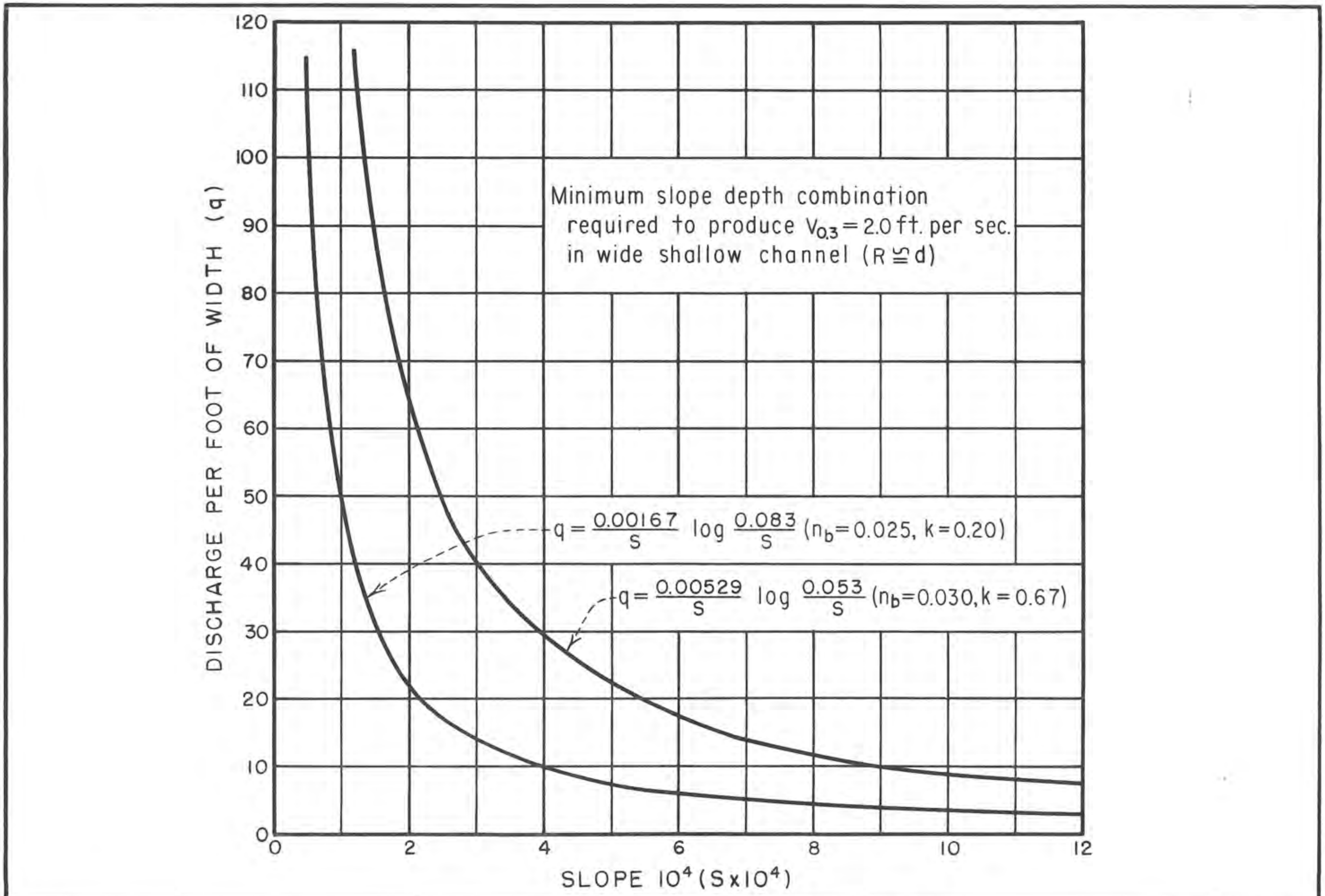
It may be of interest to cite an independent estimate of the apparent value of "n" for a roughened bed. This estimate was made by Mr. C. H. Clay, Chief Engineer, Pacific Area of the Canadian Department of Fisheries in a private communication. He used material from an unpublished paper by Professor Thysse of the Technical University of Delft. Professor Thysse develops a logarithmic formula using the factor, $a = k/2$, or half the roughness height. The factor "a" is developed for riverbeds with sand transport and waves. By adapting the formula to a spawning channel Mr. Clay obtained estimates of n_a varying from 0.0268 to 0.0275 for a channel with a hydraulic radius of 10 feet. These values compare favorably with those of 0.028 and 0.029 obtained previously.

In view of the fact that the increased value of "n" is used principally to assure that the freeboard allowance is adequate, the conservative value of 0.030 seems appropriate.



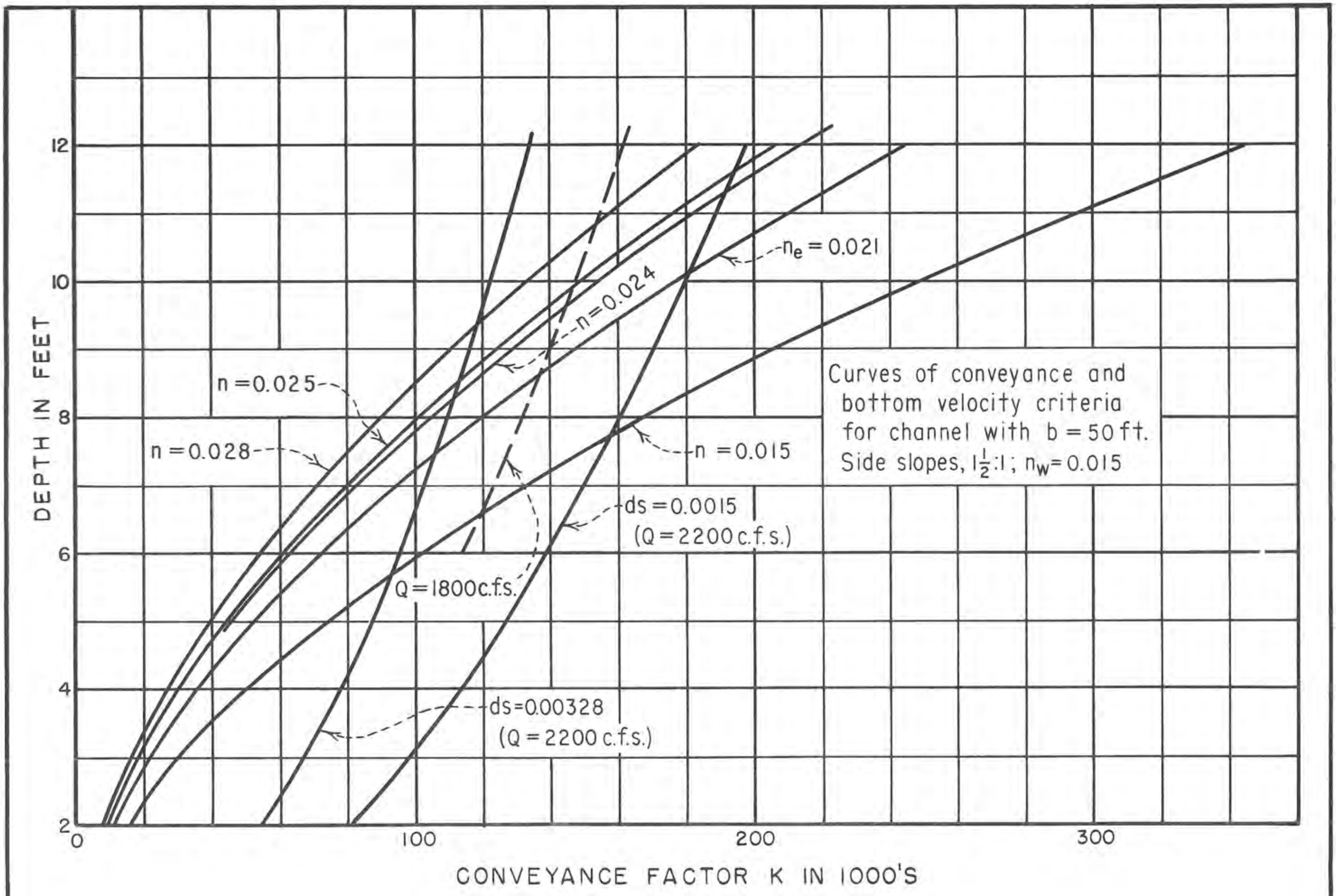
Relation between depth and slope to meet bottom velocity criterion $V_{0.3}$ = 2.0 ft. per sec. wide, shallow channel d ≅ R
ds = 0.00297
ds = .00138
DEPTH (d) IN FEET
SLOPE ($S \times 10^4$)
0
2
4
6
8
10
12
14
16

FIGURE 1



Minimum slope depth combination required to produce $V_{0.3} = 2.0$ ft. per sec. in wide shallow channel ($R \cong d$)
$q = \frac{0.00167}{S} \log \frac{0.083}{S}$ ($n_b = 0.025$, $k = 0.20$)
$q = \frac{0.00529}{S} \log \frac{0.053}{S}$ ($n_b = 0.030$, $k = 0.67$)
DISCHARGE PER FOOT OF WIDTH (q)
SLOPE 10^4 ($S \times 10^4$)
120
110
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12

FIGURE 2



Curves of conveyance and bottom velocity criteria for channel with b = 50 ft. Side slopes, 1½:1; n_W = 0.015
n_e = 0.021
n = 0.024
n = 0.025
n = 0.028
n = 0.015
ds = 0.0015 (Q = 2200 c.f.s.)
Q = 1800 c.f.s.
ds = 0.00328 (Q = 2200 c.f.s.)
DEPTH IN FEET
2
4
6
8
10
12
0
100
200
300
CONVEYANCE FACTOR K IN 1000'S

FIGURE 3

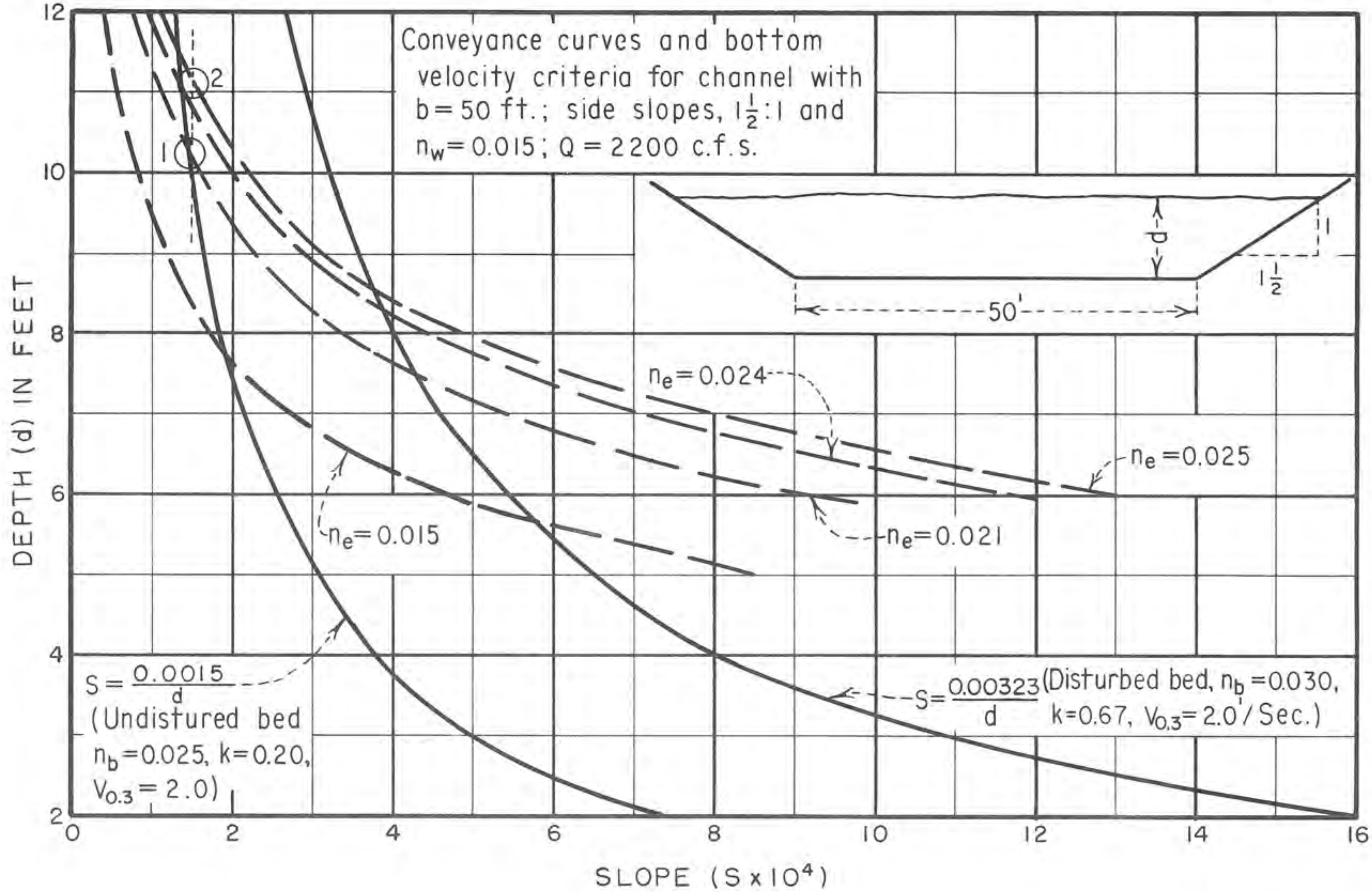
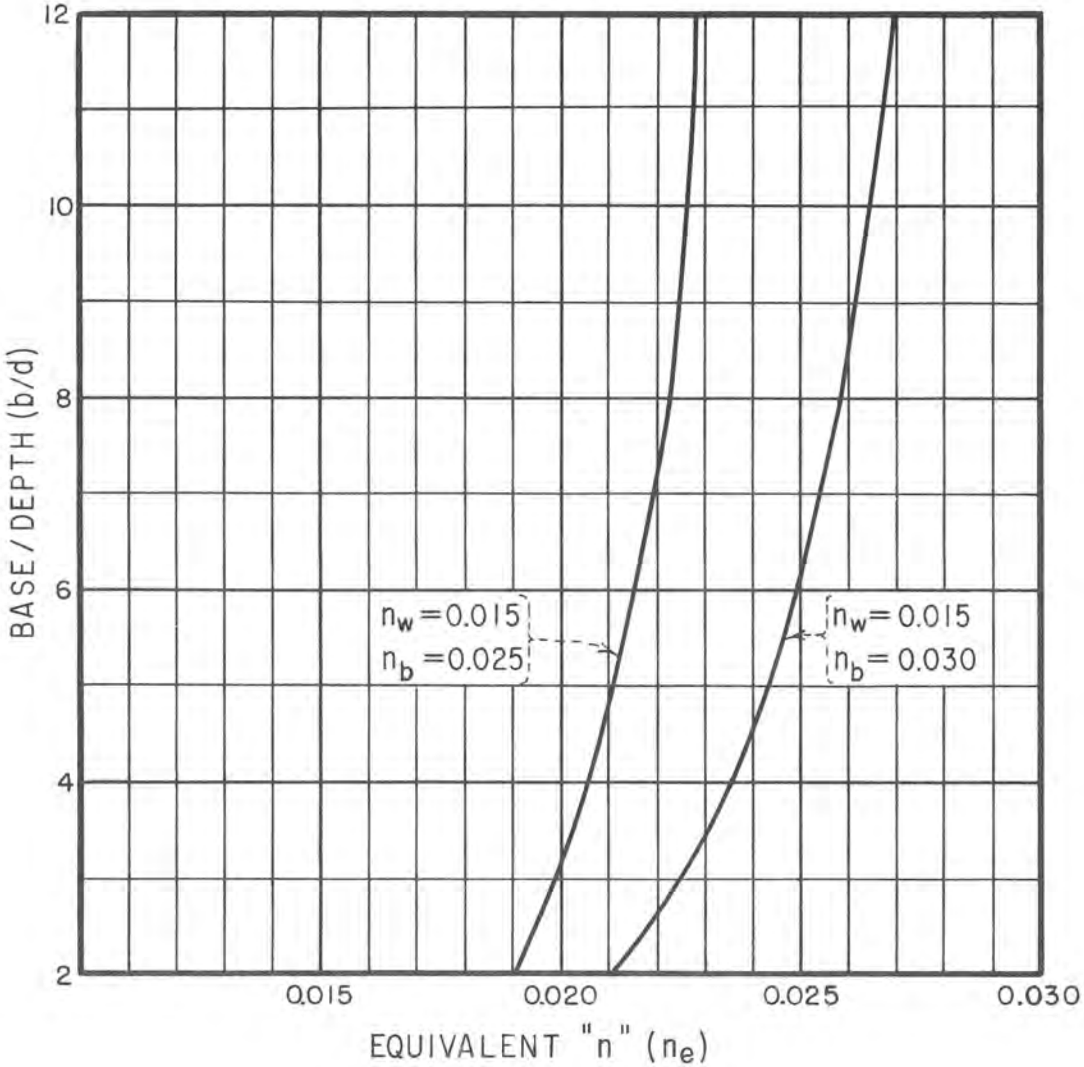

Conveyance curves and bottom velocity criteria for channel with b = 50 ft.; side slopes, 1½:1 and n_w = 0.015; Q = 2200 c.f.s.
DEPTH (d) IN FEET
SLOPE (S x 10⁴)
n_e = 0.024
n_e = 0.025
n_e = 0.021
n_e = 0.015
$S = \frac{0.0015}{d}$ (Undisturbed bed n_b = 0.025, k = 0.20, $V_{0.3}$ = 2.0)
$S = \frac{0.00323}{d}$ (Disturbed bed, n_b = 0.030, k = 0.67, $V_{0.3}$ = 2.0'/Sec.)
50'
d
1
1½
1
2
0
2
4
6
8
10
12
14
16

FIGURE 4



Equivalent "n" for $n_w = 0.015$
and different values of n_b
$Z = 1\frac{1}{2}$ to 1

b/d	n_e ($n_b = 0.025$	n_e ($n_b = 0.030$
2	0.0190	0.0210
4	0.0205	0.0235
5	0.0211	0.0243
6	0.0215	0.0249
8	0.0222	0.0258
12	0.0228	0.0269

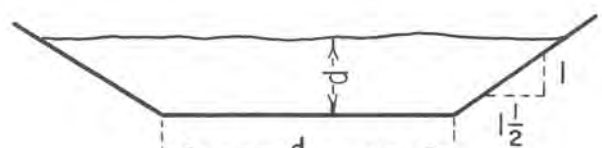


FIGURE 5

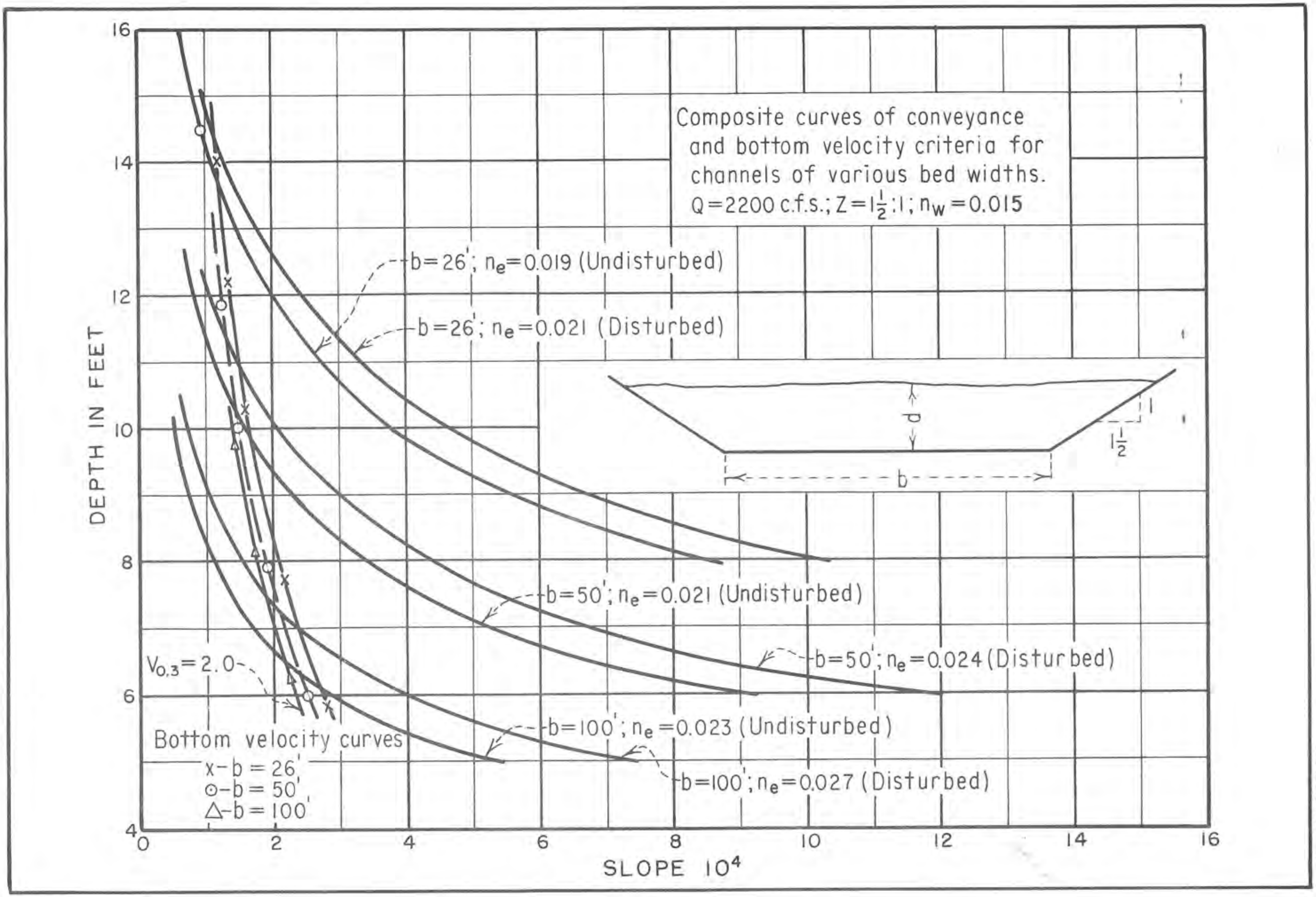

Composite curves of conveyance and bottom velocity criteria for channels of various bed widths.
Q=2200 c.f.s.; Z=1½:1; n_w=0.015
b=26'; n_e=0.019 (Undisturbed)
b=26'; n_e=0.021 (Disturbed)
b=50'; n_e=0.021 (Undisturbed)
b=50'; n_e=0.024 (Disturbed)
b=100'; n_e=0.023 (Undisturbed)
b=100'; n_e=0.027 (Disturbed)
V0.3=2.0
Bottom velocity curves
x-b=26'
⊙-b=50'
△-b=100'
d
b
1
1½
DEPTH IN FEET
SLOPE 10⁴
16
14
12
10
8
6
4
0
2
4
6
8
10
12
14
16

FIGURE 6

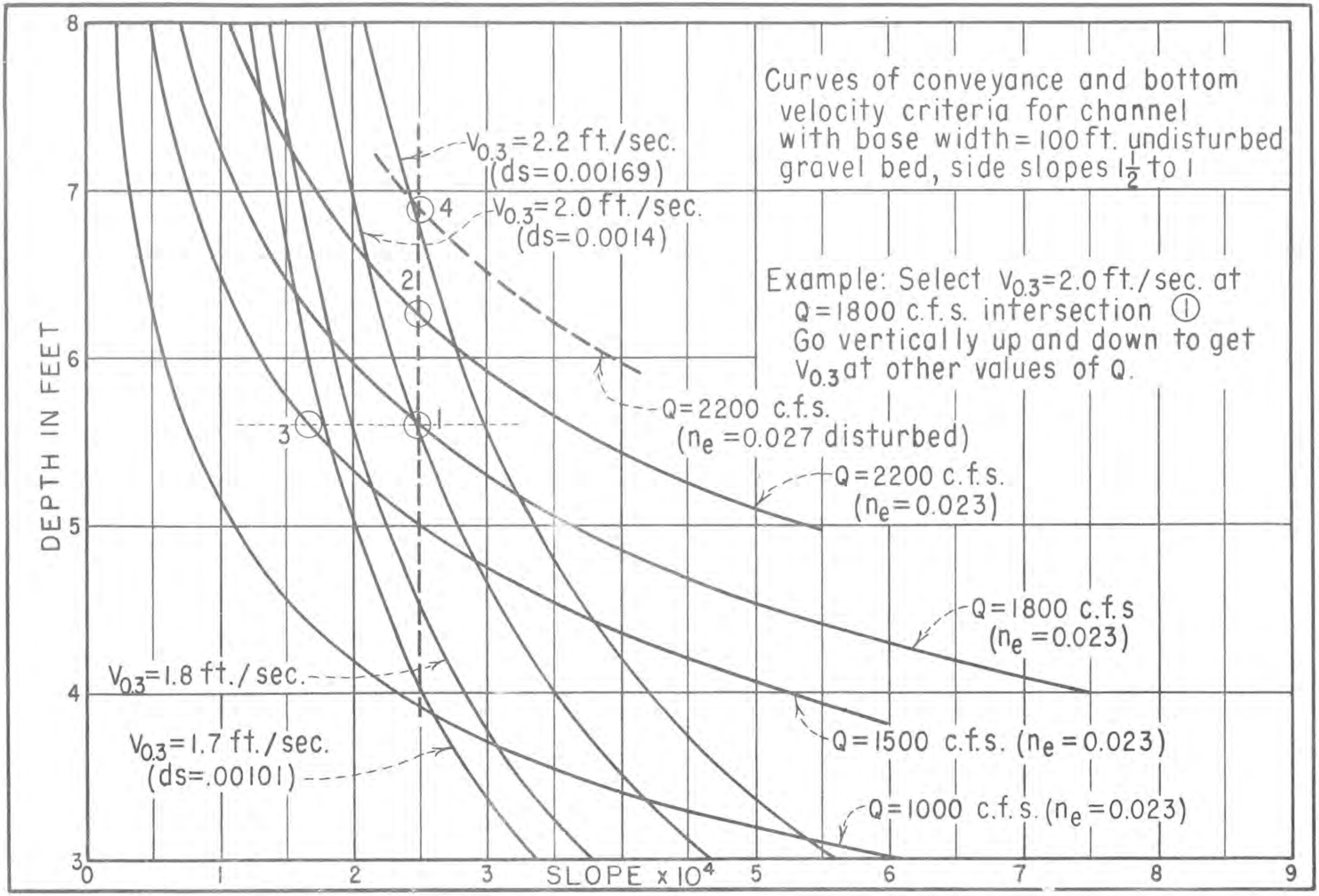

Curves of conveyance and bottom velocity criteria for channel with base width = 100 ft. undisturbed gravel bed, side slopes 1½ to 1
Example: Select $V_{0.3}$ = 2.0 ft./sec. at Q = 1800 c.f.s. intersection ① Go vertically up and down to get $V_{0.3}$ at other values of Q.
$V_{0.3}$ = 2.2 ft./sec. (ds = 0.00169)
$V_{0.3}$ = 2.0 ft./sec. (ds = 0.0014)
Q = 2200 c.f.s. (n_e = 0.027 disturbed)
Q = 2200 c.f.s. (n_e = 0.023)
Q = 1800 c.f.s (n_e = 0.023)
Q = 1500 c.f.s. (n_e = 0.023)
Q = 1000 c.f.s. (n_e = 0.023)
$V_{0.3}$ = 1.8 ft./sec.
$V_{0.3}$ = 1.7 ft./sec. (ds = .00101)
DEPTH IN FEET
SLOPE x 10^4
1
2
3
4
8
7
6
5
4
3
0
1
2
3
5
6
7
8
9

FIGURE 7