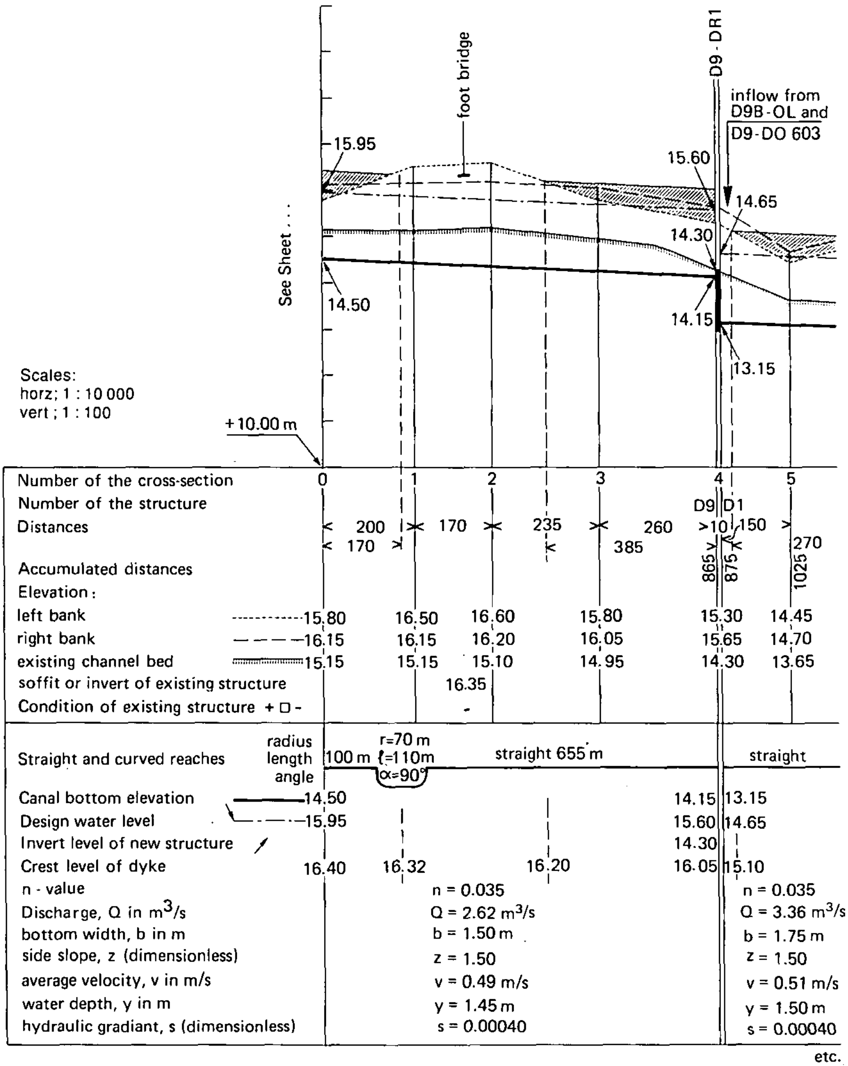

Figure 19.18 Example of a longitudinal profile

19.4 Uniform Flow Calculations

19.4.1 State and Type of Flow

The flow in the canals forming the main drainage system is very complicated because it changes as the discharge from the field drainage system changes. Moreover, the cross section of the canals is not the same along its entire length, and it contains structures that influence the flow. To simplify the computation of flow, the drainage canal system is divided into reaches between structures and canal junctions. In each reach, the discharge is considered a constant design value. This is a fair assumption in areas where the transformation of precipitation into surface runoff is slow. The computation is therefore made for the design discharge at a certain moment, the flow being uniform for this discharge. Uniform flow means that in every section of a canal reach, the discharge, area of flow, average velocity, and water depth are constant. Consequently, the energy line and the water surface will be parallel to the channel bottom (Figure 19.19). This assumption is valid except for immediately upstream of structures, where a backwater effect may occur.

In contrast with groundwater flow, flow through open channels and pipelines is nearly always turbulent. Only rarely will laminar flow appear as, for example, sheet flow over flat lands. As a criterion for the condition of flow, we use the Reynolds number, which is defined here as

$$\mathrm{Re} = \frac{vR\rho}{\eta} \tag{19.4}$$

where

ρ = mass density of water (kg/m^3)
η = dynamic viscosity (kg/m s)

For values of ρ and η see Table 7.1 of Chapter 7.

When Re is less than about 500, the flow is laminar; and when Re is larger than about 2000, the flow is turbulent. If Re ranges between 500 and 2000, flow is transitional, and may either be turbulent or laminar depending on the direction from which this transitional range is entered (Chow 1959).

The flow of water through open channels is affected by viscosity and by gravity. The effect of gravity can best be explained by the concept of energy. As stated in Section 7.2.4, water has three interchangeable types of energy per unit of volume:

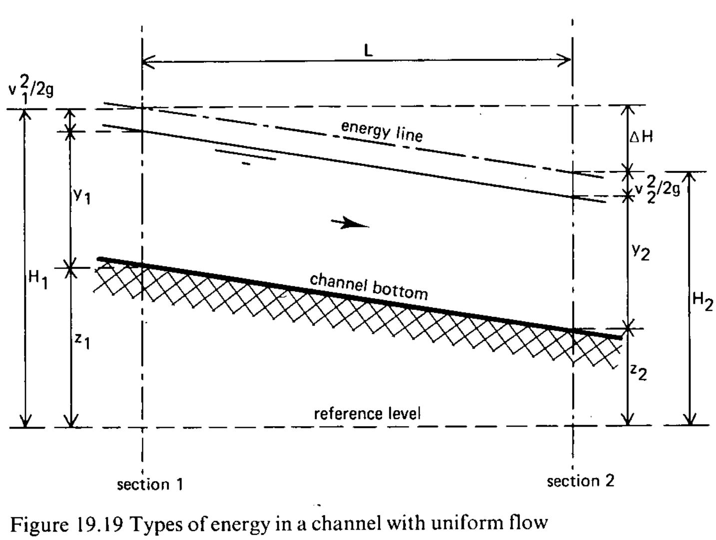

Figure 19.19 Types of energy in a channel with uniform flow

kinetic, potential, and pressure. For Section 1 of Figure 19.19 we thus may write

$$H_1 = \frac{v_1^2}{2g} + \frac{p_1}{\rho g} + z_1 \qquad (19.5)$$

where

H = total energy head (m)
g = acceleration due to gravity (m/s^2)
p = hydrostatic pressure (Pa)
z = elevation head (m)

For uniform flow the pressure under water increases linearly with depth, so the pressure head, $p_1/\rho g$, can be replaced by y_1. We can therefore write Equation 19.5 as

$$H_1 = \frac{v_1^2}{2g} + y_1 + z_1 \qquad (19.6)$$

If we express the total energy head relative to the channel bottom ($z_1 = 0$) and substitute the continuity equation

$$Q = v_1 A_1 = v A \qquad (19.7)$$

into Equation 19.6, we can write

$$H_1 = y_1 + \frac{Q^2}{2gA_1^2} \qquad (19.8)$$

where A_1, the cross-sectional area of flow, can also be expressed in terms of y_1. From Equation 19.8 we see that for a given shape of the canal cross section and a constant discharge, Q, there are two alternate depths of flow, y_1, for each energy head, H_1 (Figure 19.20). For the greater depth, y_{sub}, the flow velocity is low and flow is called subcritical; for the lesser depth, y_{super}, the flow velocity is high and flow is called supercritical. Equation 19.8 also can be presented as a family of curves, with the channel-bottom-referenced energy head and the water depth as coordinates. This is shown for one constant Q in Figure 19.21. The water depths y_{sub} and y_{super} and the related velocity heads are illustrated in Figure 19.20.

The total energy head as measured with respect to the channel bottom can be lower than that used in Figure 19.20. With a decreasing H value, the difference between y_{sub} and y_{super} becomes smaller until they coincide at the minimum possible value of

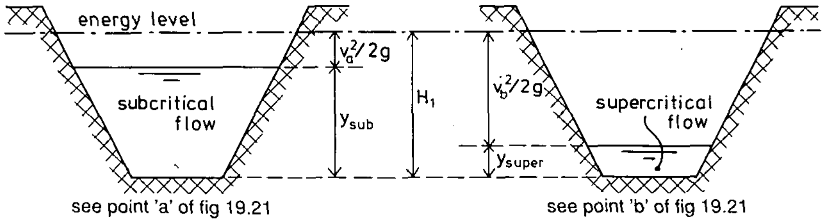

Figure 19.20 With, Q_1 and H_1, two alternate depths of flow are possible

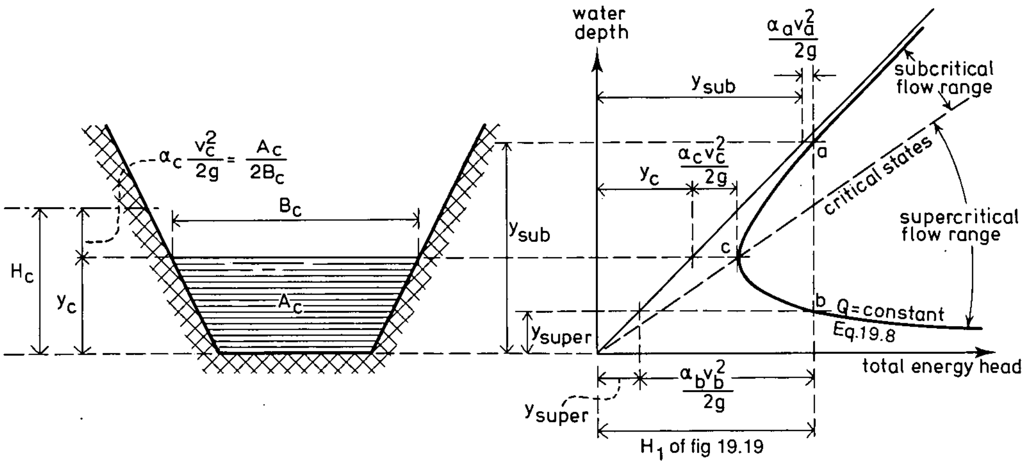

Figure 19.21 Relation between energy head and state of flow

H at which the constant discharge, Q, can be transported through the canal. When this happens, we have reached point C on the curve in Figure 19.21. The depth of flow at point C is known as 'critical depth', y_c.

When there is a rapid change in flow depth from y_{sub} to y_{super}, a steep depression called a hydraulic drop, will occur in the water surface. The water surface in the drop remains rather smooth, and energy losses over it are usually less than $0.1 v_b^2/2g$. On the other hand, if there is a rapid change of flow from y_{super} to y_{sub}, the water surface will rise abruptly, creating what is called a 'hydraulic jump', or 'standing wave'. The hydraulic jump is highly turbulent, which may cause as much as $1.2 v_b^2/2g$ of the total (hydraulic) energy to be lost to heat and noise.

From Figure 19.21 we see that if the flow is critical the channel bottom-referenced total energy head is a minimum for the constant discharge, Q. This minimum occurs if $dH/dy = 0$; thus if

$$\frac{dH}{dy} = 1 - \frac{Q^2}{gA^3}\frac{dA}{dy} = 0$$

Since $dA = B\,dy$, with B = width of the water surface in the canal, this equation becomes

$$\frac{v^2 B}{gA} = 1 \qquad (19.9)$$

The square root of the left-hand term of Equation 19.9 is the well-known 'Froude number'

$$Fr = \frac{v}{\sqrt{g\frac{A}{B}}} \qquad (19.10)$$

From the above we see that if $Fr = 1.0$, flow is critical; if $Fr > 1.0$, flow is supercritical, and if Fr < 1.0, flow is sub-critical. In earthen canals the flow velocity usually is so low that the Froude number is below 0.2. If the canal has a (pervious) lining, the flow velocity can increase without causing erosion. However, to avoid an uncontrolled hydraulic jump in a channel because of variations in v, B, or A, open channels usually are designed to flow at Fr $\leq$ 0.45.

19.4.2 Manning's Equation

The most widely used equation for calculating uniform flow in open channels is Manning's equation. It was published in 1889, and later modified to read (in metric units)

$$v = \frac{1}{n} R^{2/3} s^{1/2} \tag{19.11}$$

Because of the assumption that the resistance coefficient is dimensionless, the factor 1 of Equation 19.11 measures $m^{1/3}/s$, which is partly due to the incorporated $\sqrt{g}$ (g = acceleration due to gravity). Therefore, Equation 19.11 reads in English units

$$v = \frac{1.49}{n} R^{2/3} s^{1/2} \tag{19.12}$$

In combination with the continuity equation

$$Q = vA \tag{19.13}$$

Equation 19.11 reads

$$Q = \frac{1}{n} A R^{2/3} s^{1/2} \tag{19.14}$$

or

$$AR^{2/3} = \frac{n Q}{s^{1/2}} \tag{19.15}$$

Because we calculate the hydraulic radius from the canal dimensions to equal

$$R = \frac{A}{P} = \frac{(b + zy) y}{b + 2y\sqrt{1 + z^2}} \tag{19.16}$$

We can also write the left-hand term of Equation 19.15 as

$$AR^{2/3} = \frac{[(b + zy) y]^{5/3}}{[b + 2y \sqrt{1 + z^2}]^{2/3}} \tag{19.17}$$

To use these equations in canal design is complicated because only the tentative canal alignment and the design discharge are known. The canal alignment and Section 19.3.1 should be used to determine the available hydraulic gradient, s. The design discharge yields the Q value. The procedure to determine the remaining design parameter is as follows:

1) Use the anticipated canal depth (Table 19.2), and the collected soil mechanical information (Table 19.3) to select a side slope ratio, z;
2) Read the criterion of Section 19.3.5 on the b/y ratio. Note that for the b/y ratio, y approaches D for bank-full flow at the design capacity. Use Figure 19.17 to select a b/y value;
3) Substitute the selected values of z and b/y into Equation 19.17. This equation then reduces to

$$A\,R^{2/3} = K_b\,b^{8/3} \tag{19.18}$$

   where K_b has a constant value for each given combination of z and b/y;
4) Use Section 19.4.3 to determine a n-value for the design discharge. For vegetated channels a tentative average flow velocity must be assumed to calculate the Reynolds number. Note that the n-value generally decreases with increasing water depth because in deep channels most water flows further away from the channel bottom and sides. Hence, a higher n-value should be used for the normal (base) flow Q_n in the same canal;
5) Use the topographical map, and the canal alignment (read Section 19.3.1), to determine the available hydraulic gradient. The gradient that can be used for canal flow often will be less than this available gradient because; head loss is needed for flow through structures; the flow velocity may be too high with the available gradient;
6) Calculate the value of $AR^{2/3}$ with Equation 19.15. This value now can be substituted into Equation 19.18 to calculate the bottom width, b. Round off this b-value to, for example, the nearest 0.10 m;
7) With the z value of Step 1, and the b/y ratio of Step 2, determine the canal cross section. From this cross section the wetted area $A = (b + zy)\,y$ can be calculated;
8) Calculate the average flow velocity with $v = Q / A$.

At this stage of the calculations, the designer must check whether the calculated average velocity is pemissible (see Section 19.5). If the velocity is too high, he should repeat Step 5 to 8 with a flatter hydraulic gradient.

9) Use the above canal dimensions, and the n value for Q_n, to calculate the flow depth at normal flow. If the flow depth at this normal (base) flow is very shallow, water tends to concentrate and local erosion may occur on the (wide) canal bottom. Two solutions are available; narrow the canal bottom, or design a compound canal whereby the normal flow is concentrated in a narrow (lined) part of the cross section.

19.4.3 Manning's Resistance Coefficient

The value of n depends on a number of factors: roughness of the channel bed and side slopes, thickness and stem length of vegetation, irregularity of alignment, and hydraulic radius of the channel. The U.S. Bureau of Reclamation (1957) published a good description of channels, with their suitable n value, based on the work of Scobey. As shown below, this description gives good information if n remains below about 0.030.

n = 0.012
For surfaced, untreated lumber flumes in excellent condition; for short, straight, smooth flumes of unpainted metal; for hand-poured concrete of the highest grade of workmanship with surfaces as smooth as a troweled sidewalk with masked expansion joints; practically no moss, larvae, or gravel ravelings; alignment straight, tangents connected with long radius curves; field conditions seldom make this value applicable.

n = 0.013
Minimum conservative value of n for the design of long flumes of all materials of quality described under n = 0.012; provides for mild curvature or some sand; treated wood stave flumes; covered flumes built of surfaced lumber, with battens included in hydraulic computations and of high-class workmanship; metal flumes painted and with dead smooth interiors; concrete flumes with oiled forms, fins rubbed down with troweled bottom; shot concrete if steel troweled; conduits to be this class should probably attain n = 0.012 initially.

n = 0.014
Excellent value for conservatively designed structures of wood, painted metal, or concrete under usual conditions; cares for alignment about equal in curve and tangent length; conforms to surfaces as left by smooth-jointed forms or well-broomed shot concrete; will care for slight algae growth or slight deposits of silt or slight deterioration.

n = 0.015
Rough, plank flumes of unsurfaced lumber with curves made by short length, angular shifts; for metal flumes with shallow compression member projecting into section but otherwise of class n = 0.013; for construction with first-class sides but roughly troweled bottom or for class n = 0.014 construction with noticeable silt or gravel deposits; value suitable for use with muddy gravel deposits; value suitable for use with muddy water for either poured or shot concrete; smooth concrete that is seasonally roughened by larvae or algae growths take value of n = 0.015 or higher; lowest value for highest class rubble and concrete combination.

n = 0.016
For lining made with rough board forms conveying clear water with small amount of debris; class n = 0.014 linings with reasonably heavy algae; or maximum larvae growth; or large amounts of cobble detritus; or old linings repaired with thin coat of cement mortar; or heavy lime encrustations; earth channels in best possible conditions, with slick deposit of silt, free of moss and nearly straight alignment; true to grade and section; not to be used for design of earth channels.

n = 0.017
For clear water on first-class bottom and excellent rubble sides or smooth rock bottom and wooden plank sides; roughly coated, poured lining with uneven expansion joints; basic value for shot concrete against smoothly trimmed earth base; such a surface is distinctly rough and will scratch hand; undulations of the order of 0.025 m.

n = 0.018
About the upper limit for concrete construction in any workable condition; very rough concrete with sharp curves and deposits of gravel and moss; minimum design value for uniform rubble; or concrete sides and natural channel bed; for volcanic ash soils with no vegetation; minimum value for large high-class canals in very fine silt.

n = 0.020
For tuberculated iron; ruined masonry; well-constructed canals in firm earth or fine packed gravel where velocities are such that the silt may fill the interstices in the gravel; alignment straight, banks clean; large canals of classes n = 0.0225.

n = 0.0225
For corrugated pipe with hydraulic functions computed from minimum internal diameter; average; well-constructed canal in material which will eventually have a medium smooth bottom with graded gravel, grass on the edges, and average alignment with silt deposits at both sides of the bed and a few scattered stones in the middle; hardpan in good condition; clay and lava-ash soil. For the largest of canals of this type a value of n = 0.020 will be originally applicable.

n = 0.025
For canals where moss, dense grass near edges, or scattered cobbles are noticeable. Earth channels with neglected maintenance have this value and up; a good value for small head ditches serving a couple of farms; for canals wholly in-cut and thus subject to rolling debris; minimum value for rock-cut smoothed up with shot concrete.

n = 0.0275
Cobble-bottom canals, typically occurring near mouths of canyons; value only applicable where cobbles are graded and well packed; can reach 0.040 for large boulders and heavy sand.

n = 0.030
Canals with heavy growth of moss, banks irregular and overhanging with dense rootlets; bottom covered with large fragments of rock or bed badly pitted by erosion.

n = 0.035
For medium large canals about 50 percent choked with moss growth and in bad order and regimen; small channels with considerable variation in wetted cross section and biennial maintenance; for flood channels not continuously maintained; for untouched rock cuts and tunnels based on 'paper' cross section.

n = 0.040
For canals badly choked with moss, or heavy growth; large canals in which large cobbles and boulders collect, approaching a stream bed in character.

n = 0.050 – 0.060
Floodways poorly maintained; canals two-thirds choked with vegetation.

n = 0.060 – 0.240
Floodways without channels through timber and underbrush, hydraulic gradient 0.20 to 0.40 m per 1000 m.

Manning's resistance coefficient is reasonably reliable under the above conditions if the value of n does not exceed 0.030. Channels with vegetation often have higher n values. To determine the value for such channels we can split the n value into three components (Cowan 1956)

$$n = n_t + n_o + n_v \qquad (19.19)$$

where

n_t = grain roughness component (–)
n_o = surface irregularity component (–)
n_v = vegetal drag component (–)

The grain roughness component, n_t, has a lower limit, which accounts for the 'smooth boundary' condition. Its value is

$$n_t = 0.015\, d_m^{1/6} \qquad (19.20)$$

where

d_m = d_{50}, which is the particle-diameter (mm) at which 50% (by mass) of the material is larger than that particle-diameter.

The d_{50} value can be used provided that $d_{50} \geq 0.05$ mm. If $d_{50} < 0.05$ mm, a minimum value of 0.05 mm is used in Equation 19.20.

We can determine the surface irregularity component, n_o, with Table 19.6. For the analysis of channel stability, it is not advisable to use a n_o value higher than 0.005

Table 19.6 Surface irregularity component n_o (from U.S. Dept. of Agriculture 1954)

Degree of irregularity	Surfaces comparable to:	Surface irregularity component, n_o
Smooth	The best obtainable for the materials involved.	0.000
Minor	Good dredged channels; slightly eroded or scoured side slopes of canals or drainage channels.	0.005
Moderate	Fair to poor dredged channels; moderately sloughed or eroded side slopes of canals or drainage channels.	0.010
Severe	Badly sloughed banks of natural channels; badly eroded or sloughed sides of canals or drainage channels; unshaped, jagged and irregular surfaces of channels excavated in rock.	0.020

unless the increased form roughness is expected to be permanent. This because a greater n value implies less stress at the soil-water interface.

When the channel bed and bank are thickly covered with vegetation, part of the water flows through the vegetation at low velocities. The thickness and stem length of the vegetation influence the extent of this 'low velocity' zone, while the velocities themselves are influenced by the Reynolds number (Equation 19.4). The vegetal drag component, n_v, is an analytic expression for the test reported by Ree and Palmer (1949). Temple (1979) expressed it as

$$n_v = n_R - 0.016 \quad (19.21)$$

where

0.016 = reference soil resistance value ($n_t \approx 0.016$) for a smoothly graded, bare earth channel

n_R = retardance coefficient component (–)

Within the limits of application, Figure 19.22 gives the values of n_R as a function of vegetal retardance and the Reynolds number

$$Re_g = \frac{vR_g}{\eta} \quad (19.22)$$

with

$R_g = A_g/P_g$

P_g = grassed, wetted perimeter (m)

A_g = flow area working on P_g (m^2)

C_I = retardance curve index (see Figure 19.22)

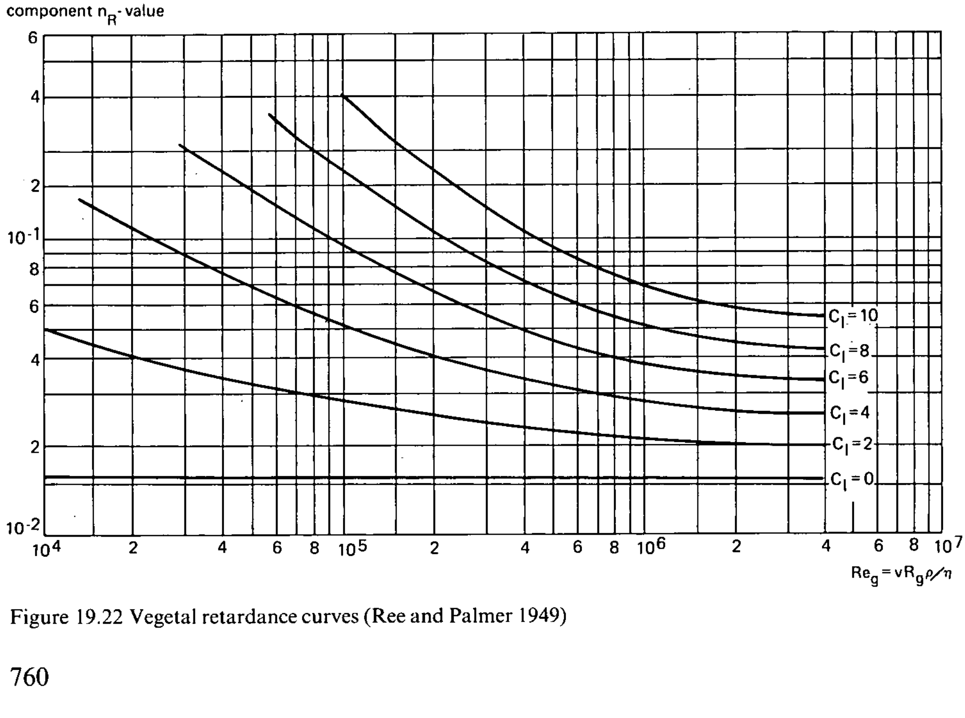

Figure 19.22 Vegetal retardance curves (Ree and Palmer 1949)

For design purposes, an engineer can take the C_I value from Table 19.7. He can also base C_I on field data by using the following equation

$$C_I = 1.63\, G_I^{0.29}\, G_{SC}^{0.12} \tag{19.23}$$

where

G_I = average stem length (m)
G_{SC} = average number of stems per m^2 (the usual count is in a square of 0.3×0.3 m)

Table 19.7 Classification of vegetal covers as to degree of retardance*

10.0	Weeping lovegrass	Excellent stand, tall (average 0.75 m)
	Yellow bluestem Ischaemum	Excellent stand, tall (average 0.90 m)
	Kudzu	Very dense growth, uncut
	Bermuda grass	Good stand, tall (average 0.30 m)
7.6	Native grass mixture (little bluestem, blue grama, and other long and short midwest grasses)	Good stand, unmowed
	Weeping lovegrass	Good stand, tall (average 0.60 m)
	Lespedeza sericea	Good stand, not woody, tall (average 0.50 m)
	Alfalfa	Good stand, uncut (average 0.25 m)
	Weeping lovegrass	Good stand, mowed (average 0.30 m)
	Kudzu	Dense growth, uncut
	Blue grama	Good stand, uncut (average 0.30 m)
5.6	Crabgrass	Fair stand, uncut (0.25 to 1.20 m)
	Bermuda grass	Good stand, mowed (average 0.15 m)
	Common lespedeza	Good stand, uncut (average 0.25 m)
	Grass-legume mixture-summer (orchard grass, redtop, Italian rye grass, and common lespedeza)	Good stand, uncut (0.15 to 0.20 m)
	Centipede grass	Very dense cover (average 0.15 m)
	Kentucky blue grass	(Good stand, headed (0.15 to 0.30)
	Bermuda grass	Good stand, cut to 0.07 m height
	Common lespedeza	Excellent stand, uncut (average 0.10 m)
	Buffalo grass	Good stand, uncut (0.07 tp 0.15 m)
4.4	Grass-legume mixture-fall, spring (orchard grass, redtop, Italian rye grass, and common lespedeza)	Good stand, uncut (average 0.10 m)
	Lespedeza sericea	Cut to 0.05 m height. Very good stand before cutting.
	Bermuda grass	
2.9	Bermuda grass	Good stand, cut to 0.04 m height
		Burned stubble.

Note: Covers classified were tested in experimental channels. Covers were green and generally uniform

* Reproduced from U.S. Department of Agriculture, Soil Conservation Service (1954), with a column added for curve index values. For Latin names of grasses, see Table 19.8

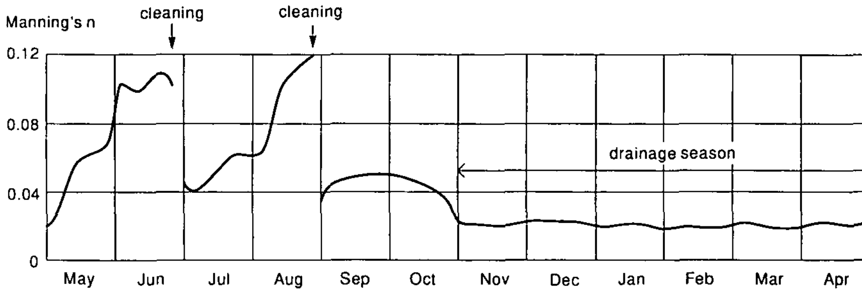

Figure 19.23 Influence of maintenance on the n value

19.4.4 Influence of Maintenance on the n Value

Equation 19.24 and Figure 19.22 show that the n value of a channel with vegetation increases as stem length increases through the growing season. Equation 19.14 shows that the discharge capacity of a channel decreases by 1/n, so that the designer has to answer the neither clear nor simple question of which n value should be used in the channel design. Fortunately, the n value of a channel with vegetation can be kept within certain reasonable limits by regular maintenance. Figure 19.23 shows how cleaning out grasses affects the n value of a drainage canal in The Netherlands. Of course, one need not base the final design on the highest probable n value. In the Dutch example of Figure 19.23, the drain discharge is highest in winter, when grasses do not grow and the n value is relatively low. The influence of maintenance is further illustrated by Photos 19.5 and 19.6.

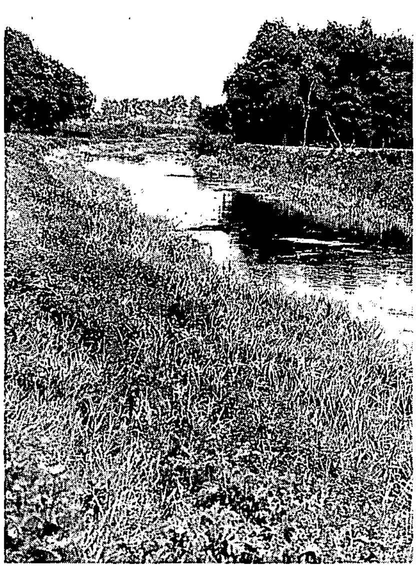

Photo 19.5 1980 Sept. 02 No maintenance since 1979
n = 0,340

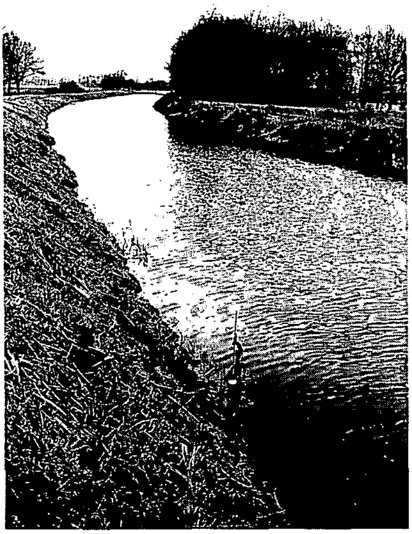

Photo 19.6 1980 Dec. 18 Some time after maintenance
$n = 0.040$ (Courtesy University of Agriculture, Wageningen)

19.4.5 Channels with Compound Sections

The cross-section of a channel may consist of several subsections, each subsection having a different roughness. For example, a main drain with a dry-season base flow and wet-season floods may have a compound cross-section like the one in Figure 19.24A. The shallow parts of the channel are usually rougher than the deeper central part. In such a case, it is a good idea to apply Manning's equation separately to each sub-area (A_1, A_2, and A_3). The total discharge capacity of the channel then equals the sum of the discharge capacities of the sub-areas.

The same can be said about trapezoidal canals, like the one in Figure 19.24B, that have thick vegetation on the banks while the earthen bottom remains clear. The flow through the areas marked A_z should then be calculated using a higher n value than the one used to calculate the flow through the area marked A_b. We can use the following relations

$$2A_z = (zy^2) + 0.2\,(by) \tag{19.24}$$

$$P_z = 2y\sqrt{z^2 + 1} \tag{19.25}$$

$$R_z = \frac{2A_z}{P_z} \tag{19.26}$$

$$A_b = A - 2A_z \tag{19.27}$$

$$P_b = b \tag{19.28}$$

$$R_b = \frac{A_b}{P_b} \tag{19.29}$$