ROUGHNESS COEFFICIENTS FOR DENSELY VEGETATED FLOOD PLAINS

By George J. Arcement, Jr. and Verne R. Schneider

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 83-4247
Reston, Virginia 1987

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

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SYMBOLS AND UNITS

Symbol	Definition	Units
A	cross-section area of channel or flow	ft^2
A_a	experimental coefficient	---
B	width of flume	ft
B_a	experimental coefficient	---
B_d	density of stems per square foot	$1/ft^2$
b	channel width	ft
$B\Delta X$	area of channel bed in the reach ΔX	ft^2
C_a	experimental coefficient	---
C_f	loss coefficient due to form drag	---
C_i	experimental coefficients	---
C_s	loss coefficient due to surface resistance	---
C_w	loss coefficient due to surface waves	---
C_*	drag coefficient	---
D	depth of flow	ft
D_a	experimental coefficient	---
D_i	drag force on ith plant	lb
d	mean depth	ft
d_s	stem diameter	ft
d_i	tree diameter	ft
E	roughness pattern constant	---
E_1	roughness pattern constant	---
E_a	experimental coefficient	---
F	Froude number	---
F_a	experimental coefficient	---

Symbol	Definition	Units
f	Darcy-Weisback resistance coefficient	---
g	gravitational constant	ft/s^2
h	depth of water on flood plain	ft
K	conveyance of the channel	ft^3/s
K_s	stiffness modulus of stem	$lb\text{-}ft^2$
L	length of channel reach	ft
l	length of representative sample area	ft
l_s	stem length	ft
m	correction factor for meandering of channel	---
N	Number of elements	---
N_s	average number of stems	---
n	Manning's roughness coefficient	$ft^{1/6}$
n_b	base value of n for a straight, uniform channel in natural materials	$ft^{1/6}$
n_o	Manning's coefficient for boundary roughness	$ft^{1/6}$
n_1	an n value for surface irregularities	$ft^{1/6}$
n_2	an n value for variations in shape and size of channel cross section	$ft^{1/6}$
n_3	an n value for obstructions	$ft^{1/6}$
n_4'	an n value for vegetation	$ft^{1/6}$
n_4	an n value used in determining n_o, representing vegetation not accounted for in vegetation density	$ft^{1/6}$
P	wetted perimeter of channel	ft
P_s	stem density per unit length of stems	1/ft
R	hydraulic radius	ft
Re	Reynolds number	---
S	bed slope of channel	ft/ft

Symbol	Definition	Units
S_e	slope of energy-grade line	ft/ft
V	mean velocity of flow	ft/s
Veg_d	vegetation density	1/ft
V_i	average approach velocity to the ith plant	ft/s
w	sample area width	ft
w_e	width of element	ft
y	depth of flow	ft
μ	fluid viscosity	slugs/ft/s
ρ	fluid density	$slugs/ft^3$
γ	specific weight of liquid	lb/ft^3
δ	roughness pattern	---
λ	roughness density	---
τ_s	shape factor defining type of stem	---
σ	roughness concentration	---
Ω	roughness element pattern	ft^2
ΣA_i	total frontal area of vegetation in the reach blocking flow	ft^2
ΣF_x	sum of the forces in the x-direction	lb
$\Sigma n_i d_i$	summation of number of trees multiplied	ft
ΔX	length of channel reach	ft
τ_w	shear force per unit area on the channel boundary	lb/ft^2
α	roughness pattern constant	---
α_1	roughness pattern constant	---

FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM OF UNITS (SI)

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per second squared (ft/s^2)	0.3048	meter per second squared (m/s^2)
inch (in.)	25.40	millimeter (mm)
square inch (in^2)	6.452	square centimeter (cm^2)
square foot (ft^2)	0.0929	square meter (m^2)
pounds per square foot (lb/ft^2)	4.882	kilograms per square meter (km/m^2)
slugs per cubic foot ($slugs/ft^3$)	515.4	kilograms per cubic meter (kg/m^3)

INTRODUCTION

There has been increasing interest and activity in flood-plain management, flood-insurance studies, and in the design of bridges and highways across flood plains. Hydraulic computations of flow for such studies require roughness coefficients, which represent the resistance to flood flows in channels and flood plains.

Although much research has been done to determine roughness coefficients for open-channel flow (Carter and others, 1963), less research has been done on determining roughness coefficients for densely vegetated flood plains, coefficients that are typically very different from those for channels.

There is a tendency to regard the selection of roughness coefficients as either an arbitrary or an intuitive process. Specific guidelines are needed to select roughness coefficients for densely vegetated flood plains so that consistent values will be selected.

The U.S. Geological Survey in cooperation with the Federal Highway Administration conducted a research study of roughness coefficients for densely vegetated flood plains. The purpose of the study was to evaluate methods of determining roughness values and to document roughness characteristics for densely vegetated flood plains. A design guide (Arcement and Schneider, 1983) was developed using the information collected for this research report.

A variety of formulas exists for computing the flow resistance for typical open-channel flow. The Manning's, the Chezy, and the Darcy-Weisback formulas are the ones most commonly used today.

Despite the limitations of the Manning's formula, as pointed out by Rouse (1965) and Carter and others (1963), it is the one used most frequently by engineers today. The Manning's formula, frequently used as a part of an indirect computation of streamflow, is

$$Q = \frac{1.49}{n} AR^{2/3} S_e^{1/2} \tag{1}$$

in which
Q = discharge, in cubic feet per second;
A = cross-section area of channel, in square feet;
R = hydraulic radius, in feet;
S_e = slope of energy grade line, in feet per feet; and
n = Manning's roughness coefficient.

Equation 1 can be rewritten so that:

$$Q = KS_e^{1/2}$$

where:

$$K = \frac{1.49}{n} AR^{2/3} \tag{2}$$

in which
K = conveyance of the channel, in cubic feet per second;
A = cross-sectional area of channel, in square feet;
R = hydraulic radius, in feet; and
n = Manning's roughness coefficient.

The term K is known as the conveyance of the channel section, and it is a measure of the carrying capacity of the channel section.

Suggested values for Manning's n, tabulated according to factors that affect roughness, are found in references such as Chow (1959), Henderson (1966), and Streeter (1971). Roughness characteristics of natural channels are given by Barnes (1967). Barnes presents photographs and cross sections of typical rivers and smaller streams with their respective n values.

For flood plains with relatively dense vegetation, Schneider and others (1977) found that values of Manning's n ranging between 0.11 and 0.18 were necessary to describe measured flood profiles using a step-backwater procedure. Ree (1958) reported n values as high as 0.18 for flow through row-planted vegetation, such as wheat and soybeans.

Ree and Crow (1977) conducted experiments over a 4-year period to determine the roughness factors for earth channels having small slopes and planted to wheat, cotton, sorghum, lespedeza, or grasses. The roughness-factor data were intended for application to the design of diversion terraces. The results of the experiments are presented according to the vegetation. Photographs and brief descriptions of the vegetation and a tabulation of the hydraulic elements are given. The reported n values can be applied directly to a channel exactly like one of those tested, but this situation usually does not happen. However, the n values reported can be used as a base to determine the roughness values in flood plains with similar vegetation.

Several of the methods previously proposed for the determination of roughness values in densely vegetated flood plains were examined. Robinson and Albertson (1952), Sayre and Albertson (1961), Koloseus and Davidian (1966), Herbich and Shulits (1964), Garton (1970), and Kowen and others (1969) all made extensive experimental studies of the resistance of open-channel flow over large, rigid roughness features. Unfortunately they were not able to develop a general relationship that could be compared to an actual field situation.

Other researchers, like Ramser (1929), Ree (1960), Petryk and Bosmajian (1975), Fenzel (1962), and Cowan (1956), have tried to develop methods of determining roughness values in densely vegetated channels.

In this research study, four approaches to the evaluation of roughness values were examined. They were a "vegetation density" method developed by Petryk and Bosmajian (1975); a "roughness concentration" analysis reported by Tseng and others (1974); a "regression analysis" developed by Garton (1970); and an "estimating procedure" suggested by Cowan (1956). In addition to presenting discussions of the above methods, this report also presents field data related to roughness coefficients of wide, densely vegetated flood plains used in the evaluation of the roughness-selection methods.

METHODS EXAMINED

Vegetation Density

The flow resistance of a vegetated flood plain is a function of many variables. Included are the flow velocity, the distribution and size of the vegetation on the flood plain, the cross-section width, the depth of flow on the flood plain, and the roughness of the flood-plain boundary.

Petryk and Bosmajian (1975) developed a procedure to determine roughness coefficients for densely vegetated flood plains by analysis of the vegetation density. This analysis uses a simple flow model. The velocity is assumed to be small enough to limit plant bending. This means the projected area of the plant in the direction of flow is independent of velocity. The analysis requires that maximum flow depth be less than the maximum height of the vegetation.

The equations were derived for steady, uniform flow, but the results may be applied to gradually varied flow. Considering a channel reach as a control volume between two cross sections (fig. 1) and using the momentum equation, the sum of the forces in the x-direction are equal to zero, or

$$\Sigma F_x = 0 \tag{3}$$

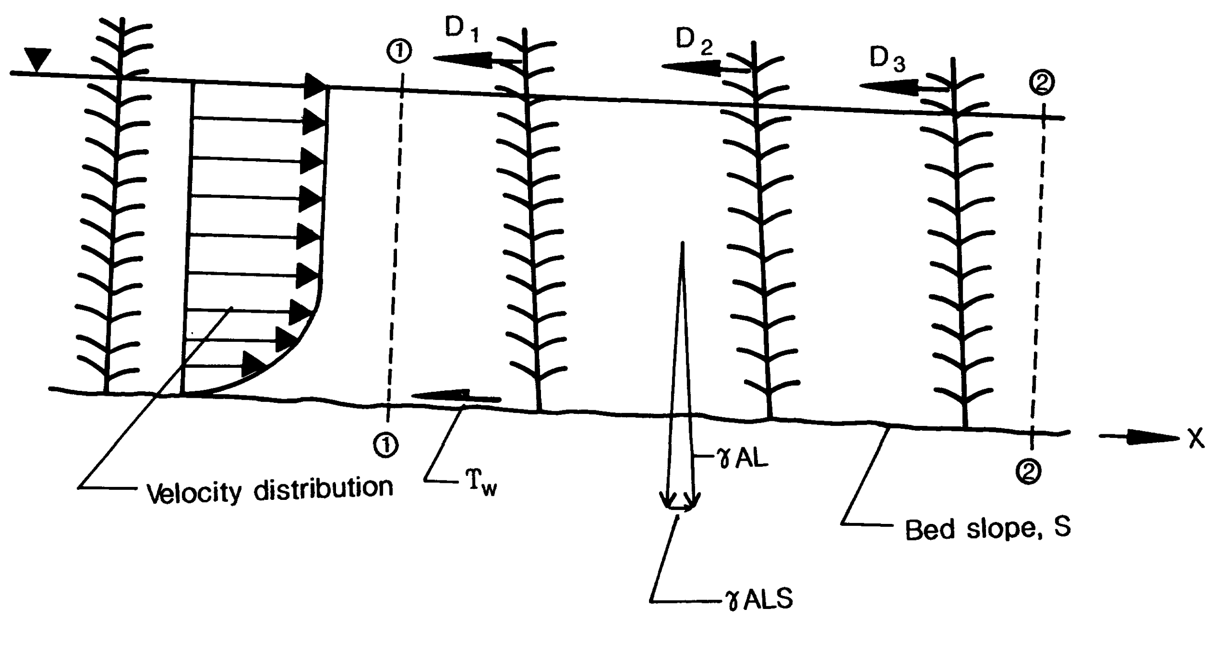


Figure 1.--Flow resistance model.

The pressure forces in the x-direction cancel, and the remaining forces are gravity, shear forces in the boundary caused by viscosity and wall roughness, and drag forces on the plants.

Equation 3 is expanded to

$$\gamma ALS - \Sigma D_i - \tau_w PL = 0 \tag{4}$$

where: γ = specific weight of liquid, in pounds per cubic foot;
A = cross-sectional area of flow, in square feet;
L = length of channel reach being considered, in feet;
S = bed slope of the channel, in feet per feet;
ΣDi = summation of drag forces on all plants, in pounds;
τ_w = the shear force on the channel boundary per unit area, in pounds per square foot; and
P = wetted perimeter of channel, in feet.

The drag force on each plant may be described by

$$D_i = \frac{C_* \gamma V_i{}^2 A_i}{2g} \tag{5}$$

where: C_* = drag coefficient for the vegetation;
V_i = average approach velocity to the ith plant, in feet per second;
A_i = projected area of the ith plant in the flow direction, in square feet; and
g = gravitational constant, in feet per second squared.

The average boundary shear stress, τ_w, is conventionally derived in the form

$$\tau_w = \gamma \left(\frac{A}{P}\right) S_e \tag{6}$$

where: Se = energy gradient due to the average shear stress on the boundary, in feet per feet.

By rewriting the Manning's formula (eq. 1) in terms of velocity and wetted perimeter, and substituting the results into equation 6, the following result is obtained for shear stress:

$$\tau_w = \gamma \left(\frac{A}{P}\right) v^2 \left(\frac{n_o}{1.49}\right)^2 \left(\frac{P}{A}\right)^{4/3}$$

or

$$\tau_w = \gamma v^2 \left(\frac{n_o}{1.49}\right)^2 \left(\frac{P}{A}\right)^{1/3} \tag{7}$$

where: V = average velocity, in feet per second; and
n_o = Manning's boundary roughness, excluding the effect of vegetation.

Substitution of equations 5 and 7 into equation 4 and assuming the approach velocity to each plant is V,

$$\gamma ALS - \frac{\gamma C_* V^2 \Sigma A_i}{2g} - \delta V^2 \left(\frac{n_o}{1.49}\right)^2 \left(\frac{P}{A}\right)^{1/3} PL = 0 \tag{8}$$

Simplifying equation 8 and solving for V^2,

$$V2 = \frac{S}{\frac{C_* \Sigma A_i}{2gAL} + \left(\frac{n_o}{1.49}\right)^2 \left(\frac{P}{A}\right)^{4/3}} \tag{9}$$

By expressing the average velocity according to the conventional Manning's formula and equating to equation 9, one obtains:

$$V^2 = \left(\frac{1.49}{n}\right)^2 S \left(\frac{A}{P}\right)^{4/3}$$

$$= \frac{S}{\frac{C_* \Sigma A_i}{2gAL} + \left(\frac{n_o}{1.49}\right)^2 \left(\frac{P}{A}\right)^{4/3}}, \tag{10}$$

in which n is the total roughness coefficient, including boundary and vegetation effects. Solving for n in equation 10 and substituting R for (A/P) the following equation results:

$$n = n_o \sqrt{1 = \left(\frac{C_* \Sigma A_i}{2gAL}\right) \left(\frac{n_o}{1.49}\right)^2 R^{4/3}} \tag{11}$$

where:

n_o = Manning's boundary roughness coefficient, excluding the effect of the vegetation;
C_* = effective drag coefficient for the vegetation in the direction of flow;
g = gravitational constant, in feet per second squared;
A = cross-sectional area of flow, in square feet;
R = hydraulic radius, in feet;
ΣA_i = total frontal area of vegetation blocking the flow in the reach, in square feet; and
L = length of channel reach being considered, in feet.

Equation 11 gives the n value in terms of the boundary roughness, n_o; the hydraulic radius, R; the effective drag coefficient, C_*; and the vegetation characteristics, $\Sigma A_i/AL$. The vegetation density, Veg_d, in the cross section is represented by the expression

$$Veg_d = \frac{\Sigma A_i}{AL} \tag{12}$$

Roughness Concentration

Tseng and others (1974) conducted experiments to determine channel resistance coefficients from artificial roughness elements representative of densely vegetated flood plains.

The energy losses of the flow in densely vegetated flood plains are due. to bed roughness, bank roughness and the resistance of bushes, plants, and trees in the flood plain.

By experimental analysis using a flume, Tseng attempted to achieve various levels of channel resistance. This resistance was related to statistical representations of spacing parameters where roughness elements are spaced randomly as well as in a regular spacing.

In turbulent flow, channel resistance is composed of many types of resistance. In a steady state, nonuniform-flow situation, Tseng showed that the total resistance force could be expressed as

$$f = (C_s + C_f + C_w) - \frac{\rho V^2}{2} \quad B\Delta X \tag{13}$$

where
C_s = loss coefficient due to surface resistance
C_f = loss coefficient due to form drag,
C_w = loss coefficient due to surface waves,
p = fluid density, in slugs per cubic foot;
V = mean velocity in direction of flow, in feet per second;
B = width of flume, in feet; and
ΔX = length of channel reach, in feet.

The C_w is difficult to define; therefore it was incorporated into surface resistance and form resistance, so that the equation becomes

$$f = (C_s + C_f) \frac{\rho V^2}{2} B\Delta X \tag{14}$$

where
$$C_s = \frac{fP}{4B}, \tag{15}$$

and
$$C_f = \frac{C_* N w_e y}{B\Delta X} \tag{16}$$

where
f = Darcy-Weisbach resistance coefficient,
P = wetted perimeter, in feet,
C_* = drag coefficient for each roughness element,
N = number of elements in the flume area $B\Delta X$,
w_e = width of element perpendicular to flow, in feet, and
y = depth of flow, in feet.

In equation 16, the expression $Nw_e y$ is the total area of the roughness elements under water, and $B\Delta X$ is the area of channel bed in the reach ΔX. The ratio of these two is defined as the concentration of roughness elements,

$$\sigma = \frac{Nw_e y}{B\Delta X}, \tag{17}$$

and

$$C_f = \sigma C_* \tag{18}$$

Tests were performed on various types of roughness elements with different combinations of patterns and spacings. The various combinations were selected to ensure a broad range of values for channel roughness. As the experiments were intended to simulate the roughness characteristics of forested flood plains, all elements were arranged to protrude through the water surface.

Three basic patterns of roughness elements were used: random, rectangular, and diamond. For each pattern, both the longitudinal and lateral spacing was varied to reflect the concentration of elements along the channel bottom.

Tseng examined the five variables listed below (eq. 19) to find their significance to flow resistance in a forested flood plain.

$$f = (F, Re, d/B, \sigma, \Omega) \tag{19}$$

where
F = Froude number,
Re = Reynolds number,
d = mean depth,
B = width of flume,
σ = roughness concentration, and
Ω = roughness element pattern.

The results showed that for a given type of roughness-element pattern, Ω, the flow resistance, f, is a unique function of the roughness concentration, σ.

The functional expression used by Tseng for any roughness pattern is

$$f = \alpha\sigma^E \tag{20}$$

or

$$n = \alpha_1\sigma^{E_1} \tag{21}$$

where α, E, α_1, and E_1 are constants for different roughness patterns.

While $\sigma = Nw_e y/B\Delta X$ is a proper expression characterizing the roughness concentration of the channel, its determination requires the prior knowledge of depth. In some cases depth is not known and is a dependent variable that must be determined. Without the knowledge of water depth, however, the roughness field can be physically represented by some type of roughness density, λ, where:

$$\lambda = \frac{Nw_e}{B\Delta X} \tag{22}$$

$$\text{and } \sigma = \frac{\lambda y}{w_e} \tag{23}$$

Roughness density is a parameter used for measuring the number of roughness elements of a typical size per unit area of channel bottom.

Estimating Procedure

Cowan (1956) developed an estimating procedure for the determination of Manning's n for natural channels. This procedure was developed assuming that realistic estimates of n could be made through the recognition of five primary factors. These basic factors are: irregularity of the surface of the channel sides and bottom; variations in size and shape of cross section; obstructions; vegetation; and meandering of channel. In this procedure, the value of n may be computed by the equation.

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m \tag{24}$$

where:
- n_b = base value of n for a straight uniform, smooth channel in natural materials;
- n_1 = value added for the effect of surface irregularities;
- n_2 = value added for variation in shape and size of the channel cross section;
- n_3 = value added for obstructions;
- n_4 = value added for vegetation; and
- m = correction factor for meandering of the channel.

The base n value will vary only with the materials forming the sides and bottom of the channel. Cowan gives suggestions for the selection of base n values for channels of different materials.

The selection of modifying values of n due to surface irregularity (n_1) is based on the degree of roughness or irregularity of the channel sides and bottom. Actual surface irregularity comparable to the best surface to be expected of the natural materials involved would call for a modifying value of zero. Higher degrees of irregularity would cause turbulence and would call for increased modifying values. Cowan describes four degrees of irregularity.

In considering changes in size of cross sections for the selection of a modifying n value (n_2), greater turbulence is associated with alternating large and small sections where changes are abrupt. Variations of cross sections should be compared to an average section. Cowan lists three different degrees of change in size and shape of cross sections.

The selection of a modifying value for obstructions (n_3) is based on the presence and characteristics of obstructions such as debris deposits, stumps, exposed roots, boulders, and fallen logs. In judging the relative effect of obstructions, consider (a) the degree to which the obstructions occupy or reduce the average cross-sectional area, (b) the character of obstructions (sharp-edged or curved and smooth-surfaced), and (c) the position and spacing of obstructions in the reach. Cowan developed a table presenting four different degrees of obstruction.

In judging the retarding effect of vegetation to determine a modifying value (n_4), consideration should be given to the following: height in relation to depth of flow; capacity to resist bending; growing-season condition versus dormant-season condition; the degree to which the cross section is occupied or blocked out; the distribution of vegetation of different types; and densities and heights in the reach under consideration. Cowan also developed a table giving different degrees of vegetation and the range of n_4 for these different degrees.

In selecting the modifying value for meandering (m), the degree of meandering depends on the ratio of the total length of the meandering channel reach to the straight length of channel reach. The meandering is considered minor for ratios of 1.0 to 1.2, appreciable for ratios of 1.2 to 1.5, and severe for ratios of 1.5 and greater. Cowan gives modifying values for each degree of meander.

Regression Analysis

Garton (1970) conducted hydraulic studies using a smooth flume in which cylindrical retardance elements were inserted at various regular spacings. The effects of the spacing pattern, diameter of the elements, spacing of the elements, slope, and flow rate on Manning's coefficient were determined.

The test procedure consisted of passing five measured flows down the test channel and making all observations needed to compute the hydraulic characteristics of the channel. Gradually varied flow was assumed. A 44-ft by 18-in. aluminum-lined flume was used. The channel was fitted with round aluminum pegs that served as roughness elements. Two sizes of elements were used, 3/32-in. and 9/32-in. diameter pegs about 3-1/2 in. long. Specific longitudinal and transverse spacing was made to form patterns known as diagonal-grid and square-grid systems.

Linear, quadratic, and exponential models were developed using dimensional analysis. Multiple-correlation coefficients that generally were greater than 0.97 were obtained. The linear-variable model and the exponential model gave slightly improved estimates, but resulted in a more complex equation to solve.

The variables considered by Garton to be pertinent in his study are listed below:

Symbol	Variables	Dimensions
n	Roughness coefficient-----------------	$L^{1/6}$
V	Mean velocity-------------------------	LT^{-1}
D	Depth of flow-------------------------	L
S	Slope of channel----------------------	---
b	Channel width-------------------------	L
L	Channel test length-------------------	L
g	Acceleration due to gravity-----------	LT^{-2}
τ_s	Shape factor defining type of stem----	---
δ	Factor denoting roughness pattern-----	---
N_s	Average number of stems/row-----------	---
B_d	Density of stem per square foot-------	L^{-2}
d_s	Stem diameter-------------------------	L
l_s	Stem length---------------------------	L
K_s	Stiffness modulus of stem-------------	FL^2
P_s	Stem density per unit length of stem-	$FL^{-2}T^2$
ρ	Fluid density-------------------------	$FL^{-4}T^2$
μ	Fluid viscosity-----------------------	$FL^{-2}T$

The general functional relations between Garton's variables can be written:

$$f(n, V, D, S, b, L, g, \tau_s, \delta, N_s, B_d, d_s, l_s, K_s, P_s, \rho, \mu) = 0 \qquad (25)$$

Garton (1970) reduced the number of variables and presented the following relation:

$$f\left(\frac{n}{R^{1/6}}, d_s B_d D, \frac{D}{b}, \frac{N_s d_s}{b}, S, \frac{V^2}{gR}\right) \qquad (26)$$

He rearranged equation 26 for convenience as follows, substituting π terms for the above variables:

$$\pi_1 = \frac{n}{R^{1/6}}, \quad \pi_2 = d_s B_d D, \quad \pi_3 = \frac{D}{b}, \quad \pi_4 = \frac{N_s d_s}{b}, \quad \pi_5 = S, \quad \pi_6 = \frac{V^2}{gR}$$

The polynomial equations developed were of the form:

Linear: $Y = C_1 + C_2X_1 + C_3X_2 + C_4X_3 + C_5X_4 + C_6X_5$

Quadratic: $Y = C_1 + C_2X_1 + C_3X_1^2 + C_4X_2 + C_5X_2^2 + C_6X_3 + C_7X_3^2$

$$+ C_8X_4 + C_9X_4^2 + C_{10}X_5 + C_{11}x_5^2$$

Where: $Y = \pi_1$, $X_1 = \pi_2$, $X_2 = \pi_3$, $X_3 = \pi_4$, $X_4 = \pi_5$, $X_5 = \pi_6$, and C_i = the experimental coefficients.

The exponential model was built from the equation,

$$\pi_1 = A_a \pi_2^{B_a} \pi_3^{C_a} \pi_4^{D_a} \pi_5^{E_a} \pi_6^{F_a}$$

where A_a, B_a, C_a, D_a, E_a, and F_a are experimental coefficents.

Values of the correlation coefficient of 0.991 and 0.981 were obtained for the diagonal and square spacing of elements, using a linear response surface for the pi-terms. When the two patterns were combined, the value was 0.967.

Using a quadratic model, the values were 0.997, 0.987, and 0.979. An exponential model yielded values of 0.991, 0.970, and 0.968.

Garton reached several conclusions from his experiments. He found that an increase in size and density of roughness elements increased the resistance of flow in the channel. Resistance to flow in the channel decreased slightly with an increase in slope, and a diagonal-grid pattern of roughness elements offered less resistance to flow then did a square grid pattern. Finally, he found that a linear model and an exponential model gave comparable results. A quadratic model gave an improved estimate, but it was more complex to calculate.

SUMMARY OF THE METHODS

All of the methods previously presented were analyzed for their suitability in determining n values for flood plains. After examination of the four methods it was determined that two, the vegetation-density method (Petryk and Bosmajian, 1975) and the roughness-concentration method (Tseng and others, 1974), were very similar. Both methods were based on the balance of the momentum equation, where the total roughness of a densely vegetated flood plain was equated to the bottom roughness plus form roughness on the flood plain. Both were derived from the force balance, where total force is equal to shear force due to form plus boundary shear force. The vegetation-density method was chosen for comparison with field data, because it determined the roughness characteristics in the form of Manning's n, and the determination of n was easily applicable to field data.

The estimation procedure of Cowan (1956) was found to be very useful in determining n values, especially for channels. The same estimation method was used by Aldridge and Garrett (1973), who attempted to systematize the selection of roughness coefficients for Arizona streams. They expanded and modified Cowan's estimation procedure.

The regression-analysis method of Garton (1970) is not applicable for field determination of n; therefore, it was not pursued any further.

COLLECTION OF DATA

Field data have been collected at the 10 sites listed in table 1, as part of a study that the Geological Survey, in cooperation with the Federal Highway Administration and the Mississippi, Alabama, and Louisiana State Highway Departments, began in 1969. The purpose of the study was to develop a method for computing backwater and discharge at width constrictions of heavily vegetated flood plains. Backwater and discharge data were collected during a 5-year period at bridges in wide, heavily vegetated flood plains in the three States mentioned above. Thirty-one floods were observed at 20 single-opening bridges. Methods to improve the accuracy of computing backwater and discharge were developed and published in a report by Schneider and others (1977).

Table 1.--Station location and date of flood for field data

Site number	Station number	Station name and location	Date of flood peak
1	02362740	Pea Creek near Louisville, Ala. Lat 31°49'08", long 85°34'08", in NW1/4 sec. 29, T. 10 N., R. 25 E., Barbour County, at bridge on County Road 27, 2.9 mi north of Louisville, Ala. (HA-608).	12-21-72
2	02367400	Yellow River near Sanford, Ala. Lat 31°19'02", long 86°21'21", in NW1/4 sec. 16, T. 4 N., R. 17 E., Covington County, at bridge on County Road 42, 2.5 mi northeast of Sanford, Ala. (HA-610).	3-12-73
3	02367490	Poley Creek near Sanford, Ala. Lat 31°19'34", long 86°18'01", in SE1/4 sec. 12, T. 4 N., R. 17 E., Covington County, at bridge on county road, 5.6 mi east of Sanford, Ala. (HA-609).	3-12-73
4	02484300	Yockanookany River near Thomastown, Miss Lat 32°51'10", long 89°39'04", in NE1/4 sec. 35, T. 12 N., R. 6 E., Choctaw Meridian, on Mississippi Highway 429, 0.8 mi east of Natchez Trace Parkway and 1.3 mi southeast of Thomastown, Miss., Leoke County (HA-599).	1- 2-70

Site number	Station number	Station name and location	Date of flood peak
5	07275700	Coldwater River near Red Banks, Miss. Lat 34°53'35", long 89°33'30", on section line between sec. 19, T. 2 S., R. 3 W., and sec. 24, T. 2 S., R. 4 W., Chickasaw Meridian, on county highway, 4.7 mi north of U.S. Highway 78 at Red Banks, Miss., Marshall County (HA-593).	2-22-71
6	07364740	Bayou de Loutre near Farmerville, La. Lat 32°52'25", long 92°23'40", on section line between sec. 20 and sec. 29, T. 22 N., R. 1 E., Louisiana Meridian, on State Highway 549, 7.0 mi north of Farmerville, La., Union Parish.	4-22-74
7	07366353	Cypress Creek near Downsville, La. Lat 32°39'32", long 92°26'35", in SW1/4 sec. 2, T. 19 N., R. 1 W., Louisiana Meridian, at bridge on State Highway 151, 2.7 mi northwest of Downsville, La., Union Parish (HA-603).	2-21-74
8	07373210	Flagon Bayou near Libuse, La. Lat 31°23'00", long 92°17'48", in NE1/4 S1/2 lot 38, T. 5 N., R. 2 E., at bridge on State Highway 116, at Esler Field Airport, 8.8 mi northeast of Pineville, La., Grant Parish (HA-604).	12- 7-71
9	07373800	Alexander Creek near St. Francisville, La. Lat 30°47'36", long 91°22'03", between lots 51 and 52, T. 3 S., R. 3 W., at bridge on State Highway 10, 1.7 mi northeast of St. Francisville, La., West Feliciana Parish (HA-600).	12- 7-71
10	07377550	Comite River at State Highway 866 near Olive Branch, La. Lat 30°42'06", long 91°03'03", in sec. 18, T. 4 S., R. 2 E., St. Helena Meridian, at bridge on State Highway 866, 2.8 mi southeast of Olive Branch, La., East Baton Rouge Parish (HA-602).	12- 7-71

In the above-mentioned study, the field data collected included peak discharge, valley cross sections, water-surface elevations, bridge geometry, and Manning's roughness coefficient, n. This information was presented in a series of Hydrologic Investigations Atlases. (See table 1.)

Field selection of Manning's roughness coefficient is usually based on experience obtained by computing water-surface profiles for channels for which peak discharge and water-surface elevations are known (n-verification studies) and by studying stereo slides that document features affecting the magnitude of n.

In the study by Schneider and others (1977), n was selected by experienced personnel (at most sites, by the same individual) to ensure consistency in the selection process. Neither published verification studies nor slides were available for comparative purposes. Therefore, the field-selected values were adjusted using the measured discharge and the recovered water-surface profile downstream of the bridge. Cross sections were subdivided according to major changes in geometry and roughness that persisted throughout a reach, and an n was selected for each subdivision. Composite n values were selected where frequent roughness changes occurred that did not affect the entire reach.

The ten sites used in this report had a relatively uniform n value for each cross section. Cross sections were selected far enough upstream and downstream from the bridge openings so that the n value was not affected by backwater. A total of 27 sample areas were measured at the 10 sites listed in table 1.

All sites had heavily wooded flood plains and were good verification sites for the vegetation-density method of determining n. Flood plains at the sites had an average slope of 6 ft/mi and an average width of 2,000 ft. The n values for the sites ranged from 0.08 to 0.18. Field data collection consisted of measuring the vegetation density of representative-sample areas along cross sections at the sites. Also, the sites were photographed (color and stereo slides) so that they could be compared to other sites.

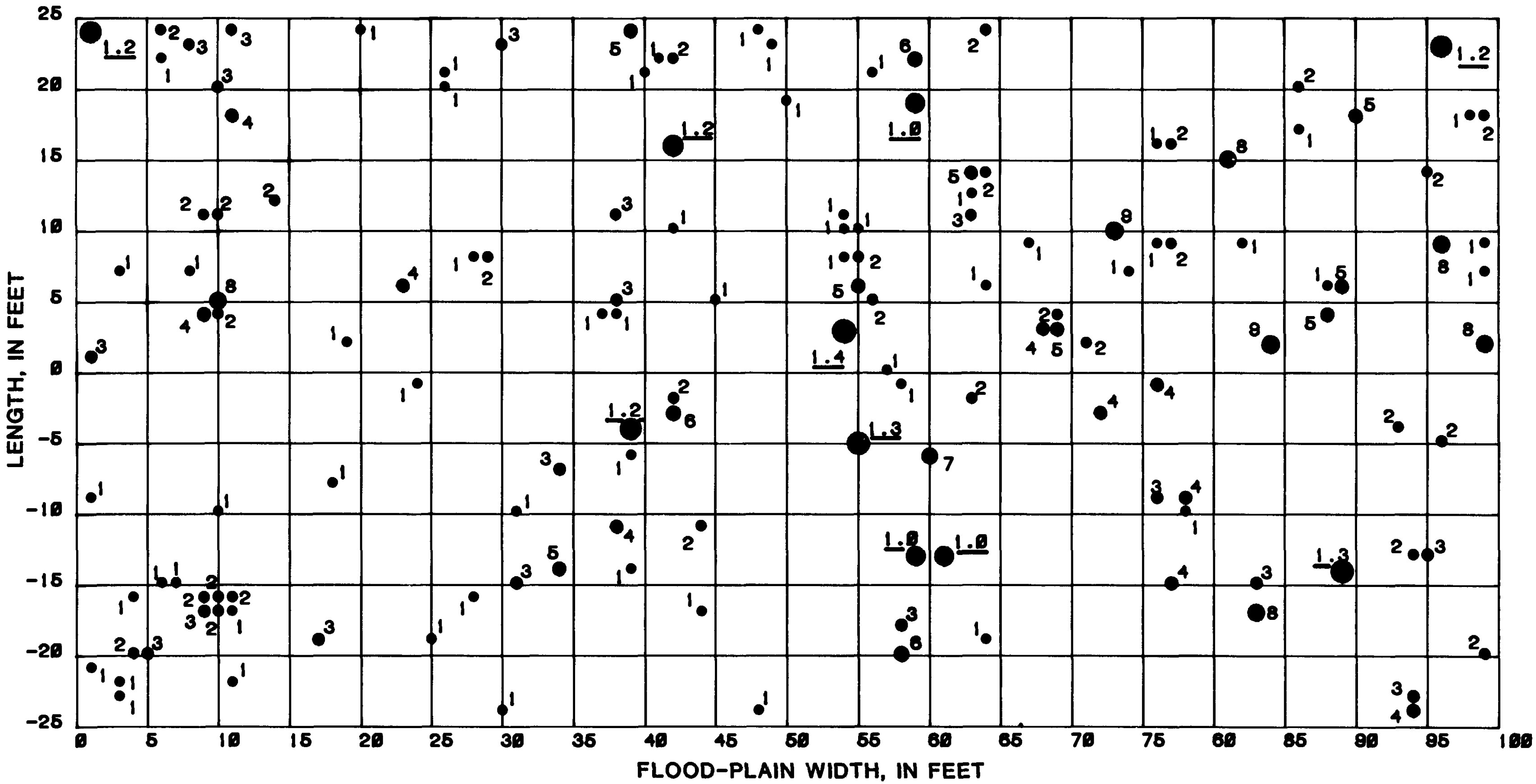
A representative sample area is a typical area that would represent the roughness of the reach being considered. Representative sample areas were chosen along cross sections at the 10 sites selected. A sampling area 100 ft along the cross section by 50 ft in the flow direction was found to be adequate to determine the vegetation density. Sampling areas of various sizes were tested and an area 100 by 50 ft was found to be the smallest area acceptable. This was determined by measuring the vegetation density of areas of different sizes at one sample site. It was found, that for sample areas less than 100 by 50 ft, the vegetation density changed for the same sites.

To determine the vegetation density of a representative sample area, the area occupied by the trees and vines in the sample area, which are major contributors to the roughness coefficient in a densely wooded flood plain, must be determined. This can be done by measuring the number of trees and large vines, their diameter, and knowing the depth of flow on the flood plain. This was done for the 27 sample areas of the 10 sites where data were collected. The position of all trees and their diameters were plotted on a grid as shown in figure 2. A general description of the representative sample area was also recorded on the grid to aid in determining base values for the

SITE: Pea Creek, cross section 2

DATE: March 13, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 40 feet tall, including many fallen trees, and some vines and ground cover. The surface is fairly smooth.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 3.

flood plain. Plots of all the representative sample areas where data were collected are shown in figures 2 and 8 to 33. The numbers by the dots in the figures are the diameters of the trees in tenths of a foot, except the numbers underlined denote the diameter of those trees in feet.

ANALYSIS OF DATA

The data used for computing n by the vegetation-density method for wide, wooded flood plains are summarized in table 2. The parameters necessary to compute n by the vegetation-density method using equation 11, are the vegetation density, Veg_d; the hydraulic radius, R; the boundary roughness of the flood plain, no; and the effective drag coefficient, C_*.

Table 2.--Summary of data used for computing n using the vegetation-density method
[Number in parentheses identifies different sampling area on same cross section. See p. v for definition of symbols]

Site number	Cross-section number	Veg_d	Hydraulic radius, R	n_b	n_1	n_3	n_o	C_*	Computed n	Verified n
1	2	0.0091	2.7	0.025	0.010	0.015	0.050	12.6	0.132	0.14
	4	.0102	2.7	.025	.010	015	.050	12.6	.138	.14
	5	.0085	2.7	.025	.005	.005	.035	12.6	.128	.14
2	2	.0091	3.6	.025	---	---	.025	8.6	.125	.13
	12	.0130	3.6	.025	---	.005	.030	8.6	.148	.13
3	2	.0115	2.9	.025	---	003	.028	11.8	.142	.13
	3	.0110	2.9	.025	---	.003	.028	11.8	.139	.13
	4	.0099	2.9	.025	---	.003	.028	11.8	.132	.13
	5	.0103	2.9	.025	---	.002	.027	11.8	.134	.13
4	300	.0087	4.0	.025	---	---	.025	6.8	.117	.12
	400	.0078	4.0	.025	---	---	.025	6.8	.111	.12
	500	.0082	4.0	.025	---	.005	.025	11.3	.111	.11
	2(2)	.0092	3.0	.020	---	.008	.028	11.3	.128	.11
	2(3)	.0090	3.0	.020	---	.008	.028	11.3	.126	.11
6	200	.0067	3.6	.025	---	---	.025	8.6	.108	.11
	300(1)	.0075	3.7	.025	---	---	.025	8.2	.113	.11
	300(2)	.0072	3.7	.025	---	---	.025	8.2	.111	.11
	400	.0063	3.7	.025	---	---	.025	8.2	.104	.11
	600	.0064	4.0	.025	.005	.005	.035	6.8	.101	.11
7	300	.0067	2.6	.025	---	---	.025	13.2	.110	.10
8	200	.0095	3.2	.025	---	---	.025	10.4	.129	.13
	300	.0126	3.0	.025	---	---	.025	11.3	.148	.13
	400	.0087	3.2	.025	---	---	.025	10.4	.124	.13
9	100	.0077	4.0	.025	.005	---	.030	6.8	.111	.14
	600	.0078	4.0	.025	.005	---	.030	6.8	.112	.14
10	200	.0054	2.0	.025	---	---	.025	16.0	.090	.07

Where trees are the major contributors to the roughness coefficient of a flood plain, as is the case of the sites considered for this project, the vegetation density can be easily determined by measuring the number of trees and trunk size in a representative sample area. The area ΣA_i occupied by trees in the sampling area can be computed from the number of trees, their diameter, and the depth of flow in the flood plain. Once the vegetation area ΣA_i is determined, the vegetation density can be computed using equation 12. Equation 12 can be simplified to,

$$Veg_d = \frac{\Sigma A_i}{AL} = \frac{h\Sigma n_i d_i}{hwl} \tag{27}$$

where $\Sigma n_i d_i$ = summation of number of trees multiplied by tree diameter, in feet;
h = depth of water on flood plain, in feet;
w = sample area width, in feet; and
l = sample area length, in feet.

The computation of the vegetation density for each representative sample area is given in table 3. Included in the table is a summary of the number of trees and their diameters for each representative sample area.

The hydraulic radius, R, is equal to the cross-sectional area of flow divided by the wetted perimeter; in a wide plain the hydraulic radius would be approximately equal to the depth of flow, because wetted perimeter would be almost equal to the width of the flood plain.

The boundary roughness, n_o, is the roughness of the flood plain excluding the effects of the trees on the flood plain. The boundary roughness, n_o, can be determined from the following equation,

$$n_o = n_b + n_1 + n_2 + n_3 + n_4' \tag{28}$$

The roughness factors n_b through n_4' can be determined by using a modification of the Cowan (1956) procedure for estimating n values for channels. The roughness factor, n_b, is a base value of n for the natural surface of the flood plain (nothing on the surface); a value can be selected from table 4. The roughness factors n_1 through n_3 are adjustment factors due to surface irregularities, variations in shape and size of flood-plain cross sections, and obstructions on the flood plain. Values for these adjustment factors can be selected using table 5.

Surface irregularities, n_1, (physical factors such as rises and depressions of the land surface and sloughs and hummocks), increase the roughness of the flood plain. The n_2 factor, which adjusts for variations in shape and size of the flood plain, is assumed to equal 0.0. The cross section of a flood plain is generally subdivided where there are abrupt changes in the shape of the flood plain. The factor for obstructions, n_3, considers contributions to roughness caused by such things as debris deposits, stumps, exposed roots, logs, or isolated boulders. The n_4' factor is the correction for vegetation (such as brush and grass, crops, or other vegetation on the flood plain) that cannot be measured directly in the Veg_d term.

Table 3.--Summary of data for computation

[Number in parentheses identifies different sampling area

Station	Cross section	Tree diameter in feet												
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
		Number of trees												
Pea Creek	2	57	28	18	10	7	4	1	5	2	2	---	4	2
	4	36	28	25	13	10	7	3	4	3	5	---	3	---
	5	51	25	18	18	9	2	2	3	4	3	---	---	---
Yellow River	2	97	35	21	6	8	4	4	6	1	---	1	2	---
	12	121	22	15	12	4	1	5	2	3	5	---	1	---
Poley Creek	2	128	65	10	9	8	7	5	6	2	3	1	---	1
	3	116	75	20	10	5	5	5	3	2	2	2	---	1
	4	86	35	17	11	4	2		1	4	6	5	1	1
	5	75	29	13	12	6	7	5	8	7	6	---	2	---
Yockanookany River	300	179	29	5	3	3	2	2	2	1	1	2	1	1
	400	82	31	11	10	5	4	1	---	---	3	---	2	1
	500	70	36	10	9	6	8	5	---	---	1	2	1	---
Coldwater River	2(1)	78	30	15	14	6	---	3	1	1	---	1	2	1
	2(2)	83	35	14	11	8	5	4	4	1	2	---	---	1
	2(3)	30	23	18	17	5	6	5	4	7	3	---	1	---
Bayou de Loutre	200	24	28	5	7	2	2	3	2	1	1	2	1	---
	300(1)	26	19	20	9	2	1	2	1	1	1	2	4	1
	300(2)	17	9	6	4	3	3	5	1	5	5	2	1	1
	400	11	14	16	15	---	2	---	2	2	---	1	1	---
	600	15	8	11	5	5	5	1	1		1		1	2
Cypress Creek	300	57	23	17	13	9	4	4	1	---	2	---	---	---
Flagon Bayou	200	223	19	6	3	4	2	2	2	2	---	1	2	2
	300	198	62	32	9	3	5	2	2	4	---	2	---	1
	400	38	38	19	11	4	1	4	6	2	1	6	2	---
Alexander Creek	100	46	32	9	11	3	---	3	2	2	2	2	2	1
	600	35	31	14	12	9	1	4	1	5	1	---	---	1
Comite River	300	11	27	4	8	7	4	3	3	---	1	---	---	---

of vegetation density at sample areas

on same cross section. See p.v for definition of symbols]

Tree diameter in feet--continued														
1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.2	2.3	2.7	3.0	3.4	$n_i d_i$ (ft)	Sample area (ft^2)	Vegetation density
Number of trees--continued														
1	---	1	---	---	---	---	---	---	---	---	---	45.5	5,000	0.0091
---	1	1	---	---	---	---	---	---	---	---	---	51.0	5,000	.0102
---	1	---	---	---	---	1	---	---	---	---	---	42.3	5,000	.0085
---	---	---	---	---	1	---	---	---	---	---	---	45.7	5,000	.0091
---	---	---	---	---	---	---	---	---	---	---	---	42.4	3,250	.0130
1	---	---	---	---	---	---	---	---	---	---	---	57.5	5,000	.0115
---	---	---	---	---	---	---	---	---	---	---	---	55.2	5,000	.0110
1	1	---	---	---	---	---	---	---	---	---	---	49.6	5,000	.0099
---	---	---	---	---	---	---	---	---	---	---	---	51.3	5,000	.0103
1	1	---	---	1	---	---	---	---	---	---	---	43.4	5,000	.0087
1	1	---	---	---	---	1	---	---	---	---	---	38.9	5,000	.0078
2	---	1	---	---	---	---	---	---	---	---	---	40.9	5,000	.0082
---	2	---	---	---	---	---	---	---	---	---	---	38.5	5,000	.0077
---	1	1	1	---	---	---	---	---	---	---	---	45.9	5,000	.0092
---	---	---	---	---	---	1	---	---	---	---	---	45.1	5,000	.0090
---	---	---	2	1	---	1	---	---	---	1	---	33.7	5,000	.0067
---	---	---	1	---	---	---	---	---	---	1	---	37.6	5,000	.0075
2	2	1	---	---	---	---	---	---	---	---	---	36.1	5,000	.0072
1	1	2	1	---	---	---	1	---	---	---	---	31.6	5,000	.0063
---	3	---	---	---	---	2	---	---	---	---	1	32.1	5,000	.0064
---	1	---	---	---	---	---	---	---	---	---	---	33.4	5,000	.0067
2	---	1	---	---	---	---	---	---	---	---	---	47.6	5,000	.0095
1	1	---	---	---	---	---	---	---	---	---	---	62.9	5,000	.0126
---	---	---	---	---	---	---	---	---	---	---	---	43.5	5,000	.0087
1	---	1	---	---	---	---	---	---	1	---	---	38.7	5,000	.0077
1	---	---	1	1	---	---	---	---	---	---	---	39.1	5,000	.0078
---	---	---	1	2	---	---	---	1	---	---	---	27.2	5,000	.0054

Table 4.--Base values of Manning's n

[Modified from Aldridge and Garrett, 1973, table 1]

Channel or flood-plain type	Median size of bed material: Millimeters	Median size of bed material: Inches	Base n value: Benson and Dalrymple[1] (1967)	Base n value: Chow[2] (1959)
Sand channels				
(Only for upper regime flow where grain roughness is predominant.)	0.2	-----	0.012	-----
	.3	-----	.017	-----
	.4	-----	.020	-----
	.5	-----	.022	-----
	.6	-----	.023	-----
	.8	-----	.025	-----
	1.0	-----	.026	-----
Stable channels and flood plains				
Concrete----------	-----	-----	0.012-0.018	0.011
Rock cut----------	-----	-----	-----	.025
Firm soil---------	-----	-----	.025- .032	.020
Coarse sand-------	1- 2	-----	.026- .035	-----
Fine gravel-------	-----	-----	-----	.024
Gravel------------	2- 64	0.08- 2.5	.028- .035	-----
Coarse gravel-----	-----	-----	-----	.026
Cobble------------	64-256	2.5 -10.1	.030- .050	-----
Boulder-----------	>256	>10.1	.040- .070	-----

[1]Straight uniform channel.
[2]Smoothest channel attainable in indicated material.

An effective-drag coefficient, C_*, is needed in equation 11. The effective-drag coefficient should be calculated from available field and laboratory data. Therefore, C_* needs to be related to a measurable variable, such as Veg_d or hydraulic radius. Figure 3 is a plot of C_* versus hydraulic radius. C_* was calculated for each of the sampling sites using equation 11. By re-arranging equation 11,

$$C_* = \frac{(n^2 - n_o^2) \cdot (29.0)}{(Veg_d)\ R^{4/3}} \qquad (29)$$

The C_* was computed using the verified n value for the sampling sites (Schneider and others, 1975), estimating the roughness factors to determine n_o (eq. 28), measuring the Veg_d (table 3), and estimating the hydraulic radius.

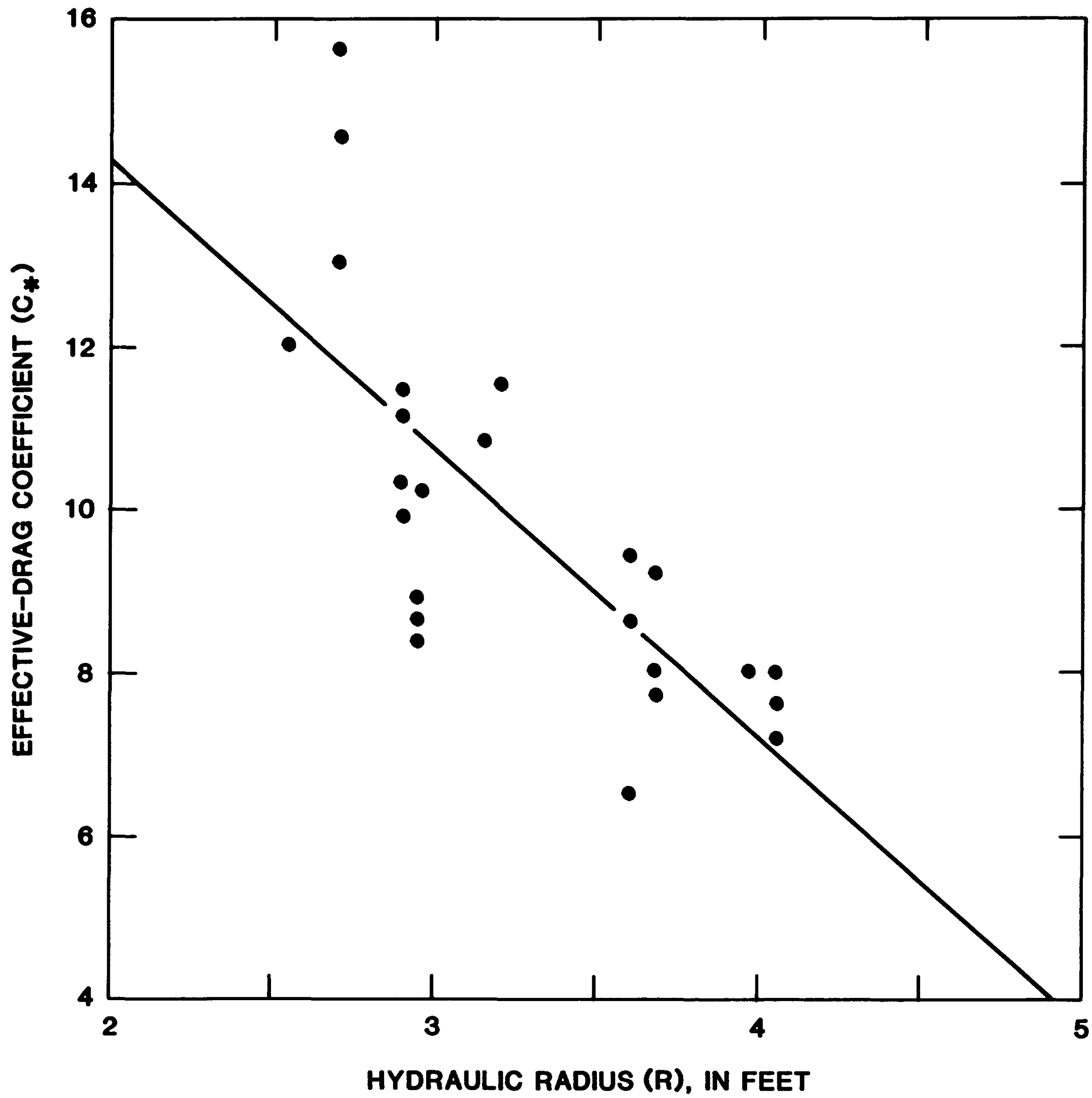


Figure 3.--Plot of effective-drag coefficient versus hydraulic radius for wide, wooded flood plains using verified n values.

The procedures presented to determine n using the Veg_d method (eq. 11) are recommended for determining n values for any wide, wooded flood plain.

DISCUSSION OF RESULTS

Figure 4 is a plot of the computed n value, using the vegetation-density method, versus the verified n value for the densely wooded flood-plain sites listed in table 2. Comparison of the computed n to the verified n shows that

Table 5.--Factors that affect roughness of flood plains

[Modified from Aldridge and Garrett, 1973, table 2]

Flood plain conditions		n value adjustment	Example
	Smooth	0.000	Comparable to the smoothest, flattest flood plain attainable in a given bed material
Degree of irregularity (n_1)	Minor	0.001-0.005	A flood plain with minor surface irregularities. A few rises and dips or sloughs may be visible on the flood plain.
	Moderate	0.006-0.010	Has more rises and dips. Sloughs and hummocks may occur.
	Severe	0.011-0.020	The flood plain is very irregular in shape. Many rises and dips or sloughs are visible. Irregular ground surfaces in pasture land and furrows perpendicular to the flow are also included.
Variation of the flood-plain cross section (n_2)		0.0	Not applicable.
	Negligible	0.000-0.004	A few scattered obstructions, which include debris deposits, stumps, exposed roots, logs, or isolated boulders, occupy less than 5 percent of the cross-sectional area.
Effect of obstructions (n_3)	Minor	0.005-0.019	Obstructions occupy less than 15 percent of the cross-sectional area.
	Appreciable	0.020-0.030	Obstructions occupy from 15 to 50 percent of the cross-sectional area.

	Small	0.001-0.010	Dense growth of flexible turf grass, such as Bermuda, or the vegetation; or weeds growing where the average depth of flow is at least two times the height of the vegetation; or supple tree seedlings such as willow, cottonwood,arrowweed, or saltcedar growing where the average depth of flow is at least three times the height of the vegetation.
	Medium	0.011-0.025	Turf grass growing where the average depth of flow is from one to two times the height of the vegetation; moderately dense stemmy grass, weeds, or tree seedlings growing where the average depth of flow is from two to three times the height of the vegetation; brushy, moderately dense vegetation, similar to 1- to 2-year-old willow trees in the dormant season.
Amount of vegetation n_4	Large	0.025-0.050	Turf grass growing where the average depth of flow is about equal to the height of vegetation; or 8- to 10-year-old willow or cottonwood trees intergrown with some weeds and brush (none of the vegetation in foliage) where the hydraulic radius exceeds 2 ft; or mature row crops such as small vegetables; or mature field crops where depth of flow is at least twice the height of the vegetation.
	Very large	0.050-0.100	Turf grass growing where the average depth of flow is less than half the height of the vegetation; or moderate to dense brush; or heavy stand of timber with few down trees and little undergrowth with depth of flow below branches; or mature field crops. where depth of flow is less than height of the vegetation.
	Extreme	0.100-0.200	Dense bushy willow, mesquite, and saltcedar (all vegetation in full foliage); or heavy stand of timber, few down trees, depth of flow reaching branches.
Degree of meander (m)		1.0	Not applicable.

the vegetation-density method for computing n values for densely wooded flood plains works quite well. The standard error determined for the computed n versus verified n was 0.92.

It is relatively easy to determine the vegetation density of a wooded flood plain. By measuring the number and diameter of the trees in a representative sample area, the Veg_d can be computed using equation 27. The n_o factor for boundary roughness can be determined using tables 2 and 3, and the hydraulic radius can be estimated or computed. The effective-drag coefficient, C_*, can be selected from figure 3.

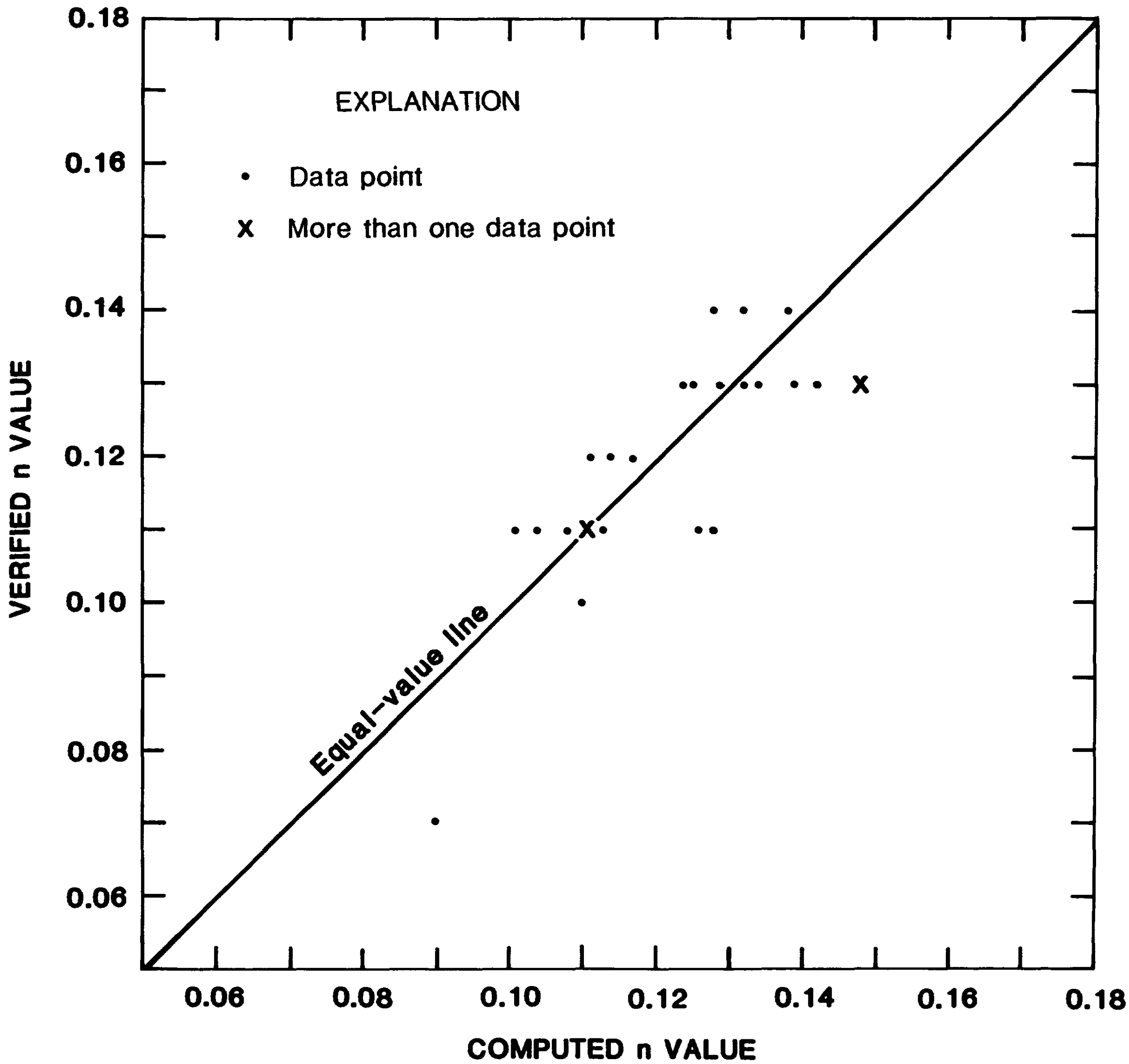


Figure 4.--Plot of computed n by vegetation-density method versus verified n values.

The magnitude of C_* in figure 3 seems to be very high when compared to other research data available. Most research indicates that C_* should be near 1.0 for flow around cylinders, but the values computed for the wooded flood-plain sites indicate that the C_* value should be around 10. A comparison of the data collected for this report to data collected by Tseng (1974) was made to help understand the differences in the C_* values.

The vegetation density, Veg_d, for a wooded flood plain can be determined using equation 27, where $Veg_d = h\Sigma S n_i d_i / hwl$. Tseng's definitions of σ and λ, as shown in equations 30 and 31, have been modified to account for the varying tree size. Tseng's roughness concentration parameter, σ, can be defined in terms of the notation used in this report as

$$\sigma = \frac{R\Sigma n_i d_i^2}{wl} \tag{30}$$

An additional parameter, a roughness-spacing parameter (λ), is defined as

$$\lambda = \frac{\Sigma n_i d_i^2}{wl} \tag{31}$$

Tseng used elements of the same size in diamond, rectangular, and random patterns. Roughness elements at the sites where the field data were collected for this report could be considered comparable to Tseng's random patterns but with elements (trees) of various sizes.

Using equations 30 and 31, σ and λ were computed for the field data and the results were compared to Tseng's (1974) flume data. As shown in figure 5, the field data plot well to the left of the flume data. The n values are comparable, but the roughness concentration and the roughness spacing are an order of magnitude lower than in Tseng's data. The scatter in the field data may be because the surface roughness in the field varied, whereas the surface roughness in the flume was constant. In addition to the varying surface roughness and the varying element size, the depth of flow was much larger in the field. Depth varied from 0.296 to 1.169 ft in the lab, and from 2.0 to 5.0 ft in the field.

Another explanation for the difference may lie in the formulation used. Tseng (1974, p. 74) computed the drag coefficient C_* from the definition:

$$C_* = \frac{S_e y}{\sigma \left(\frac{V^2}{2g}\right)} \tag{32}$$

where: S_e = the energy gradient, in feet per feet;
y = the depth of flow, in feet;
σ = the roughness concentration of the channel,
V = the mean velocity of flow in the channel, in feet per second;
and g = the gravitational constant, in feet per second squared.

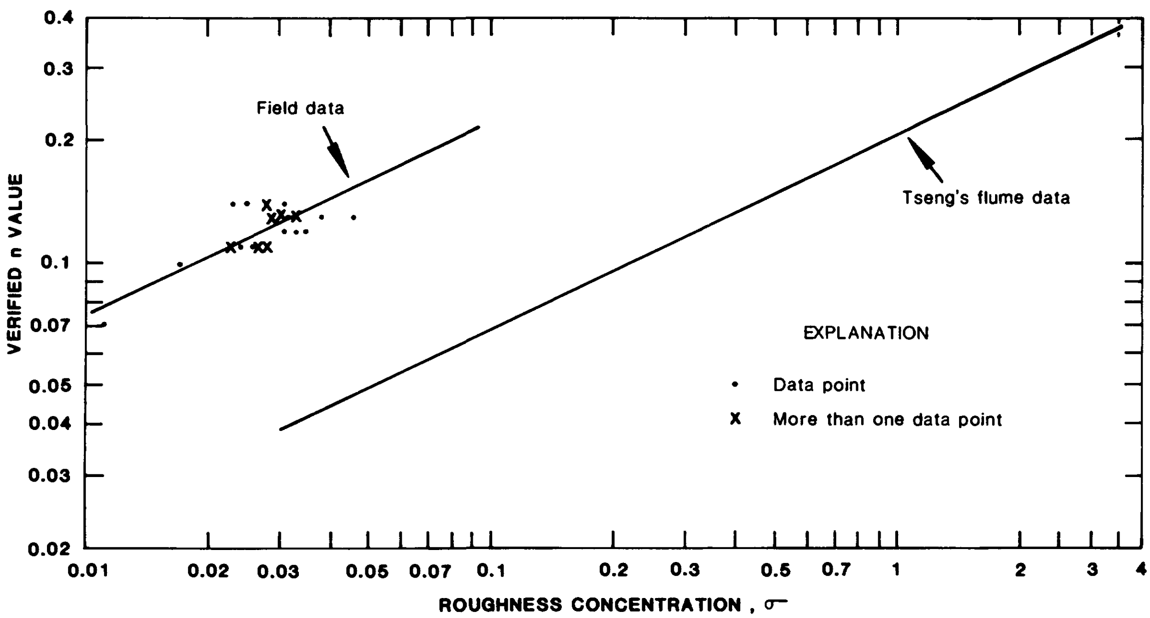


Figure 5.--Plot of n versus roughness concentration using Tseng's flume data and field data.

Tseng (1974) suggests that the values shown in table 6 can be used to compute the channel resistance. Further, he recommends use of C_* to compute resistance for forested flood plains. To evaluate this suggestion, the effective resistance (boundary resistance plus the form drag of the trees), n_e, was computed as suggested by Tseng. Tseng gave the following equation to determine the effective channel resistance of a wooded flood plain:

$$f_e = f + C_* \sigma \tag{33}$$

where f_e = effective channel resistance;
f = the Dercy-Weisbach resistance coefficient;
C_* = the drag coefficient; and
σ = roughness concentration of the wooded flood plain.

Table 6.--Tseng's drag-coefficient data

Element shape	Reynolds number, Re	Drag coefficient, C_*
●	0.6 to $1X10^3$	1.25
◆	$6X10^3$	2.0
◖	$5X10^3$	1.38
❯	$2.5X10^3$	3.20

By converting f to the Manning's n, using Chezy's formula (Chow, 1959, p. 100), the following equation can be used to compute effective resistance values for the field data (using Tseng's development and a $C_* = 1.25$, as suggested by his research).

$$\frac{116 n_e^2}{R^{1/3}} = \frac{116 n^2}{R^{1/3}} + 4C_*\sigma \tag{34}$$

The results in figure 6 show that the C_* values suggested by Tseng cannot be used. The explanation is in the formulation. An evaluation of Tseng's equation 33 with Petryk's equation 11 for n shows that the two equations are identical. Both Tseng and Petryk assume that:

Effective roughness = bottom roughness + form roughness (35)

The effective roughness is derived from the force balance where:

Total force = shear force due to form + boundary shear force (36)

Both methods presume that a roughness coefficient representative of the bed will be used in the bottom roughness term. To balance equation 36, an effective drag coefficient, C_*, is needed. Such a C_* was computed from Petryk's method for the field data and is shown in figure 3. Similarly, a C_* value was computed for Tseng's (1974) data for the random pattern, assuming that the surface roughness was small for the flume, (adapting eqs. 32 and 34) where

$$C_* = \left(\frac{1}{4s}\right)\left(\frac{116 n_e^2}{R^{1/3}}\right) \tag{37}$$

These data are shown in figure 7.

In figures 3 and 7 the effective-drag coefficient decreases as hydraulic radius increases. Tseng found that the resistance coefficient, f, increases with increasing depth. This is equivalent to C_* decreasing with R increasing. Tseng stated that in the case of protruding elements the flow resistance is

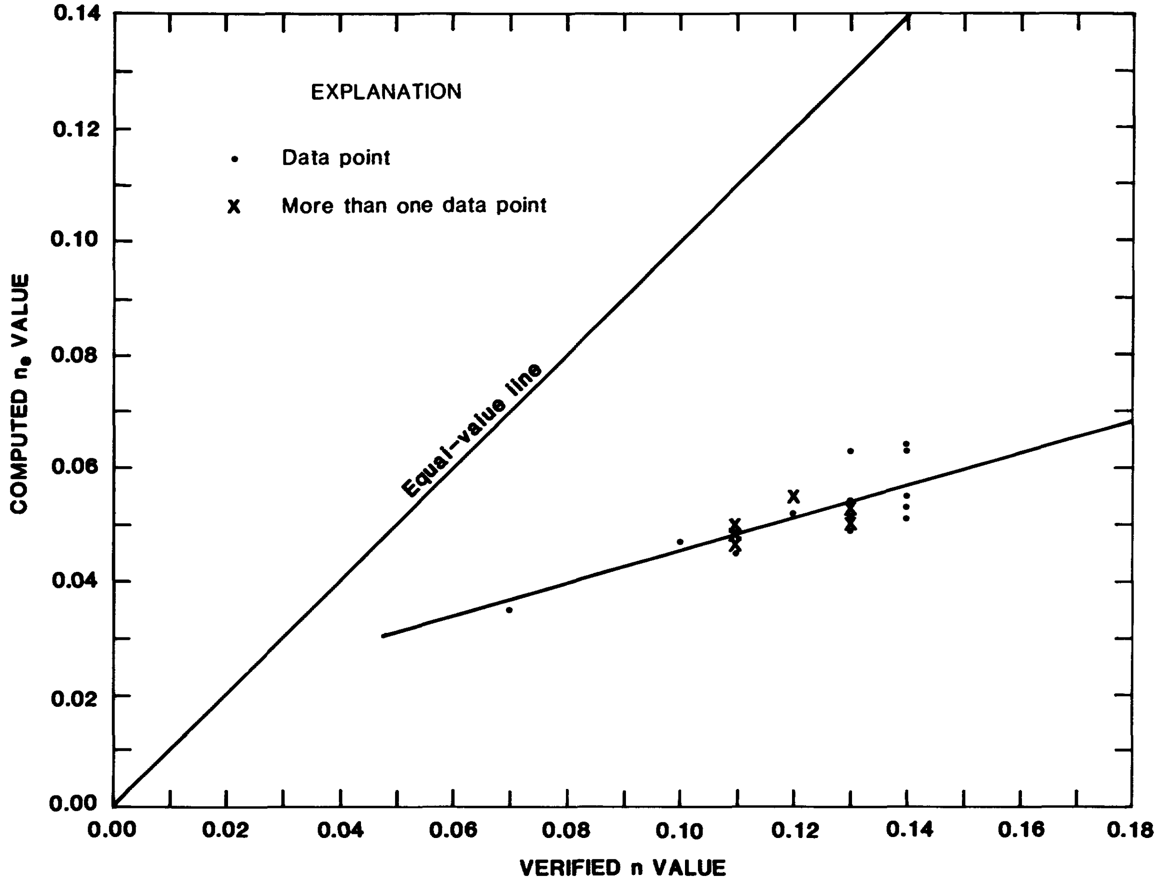


Figure 6.--Plot of effective resistance using field data and a $C_* = 1.25$.

proportional to the projected area of the roughness elements, which is proportional to the depth of flow.

One reason for the wide variance of C_* between the Petryk method and Tseng method may be related to the range of vegetation densities associated with the field data and flume data. In the flume data collected by Tseng, the vegetation density has a range of 2.316 to 0.231, which is much higher than in the field data, which has a range of 0.0130 to 0.0054.

To use either method, it is necessary to define a set of C_* values. If a set can be defined, in general, and related to measurable properties of the roughness, then it is possible to calculate n. There is a definite need for more field data to determine the range of C_*. However, the vegetation densities and the C_* values determined from the field data are representative of true field situations and are much more realistic than the roughness concentration used in the flume experiments.

Although the verification data were collected in a three-State area in the Gulf Coastal Plain, the vegetation-density method should be applicable to any wide, densely wooded flood plains.

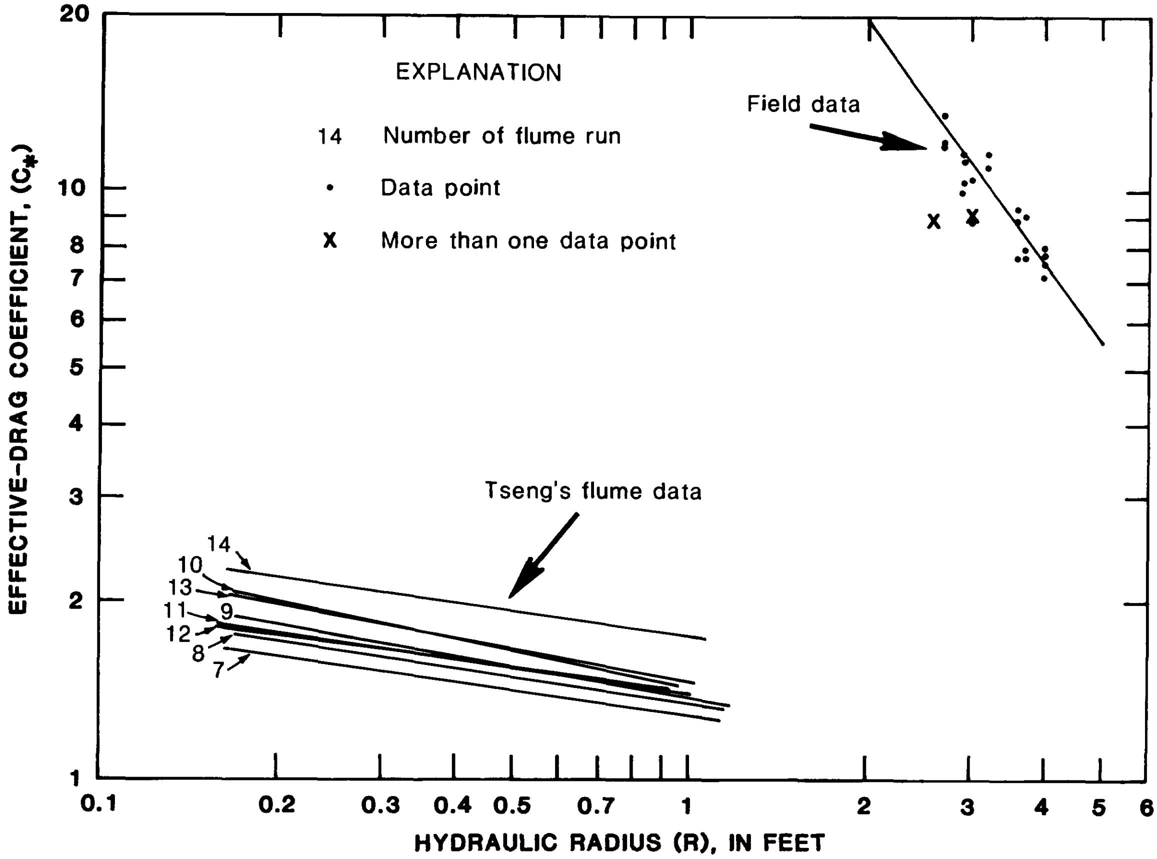


Figure 7.--Plot of effective-drag coefficient versus hydraulic radius using Tseng's flume data and field data.

CONCLUSIONS

Several methods of determining n values for flood plains were evaluated. Two of the methods, vegetation density and estimation, were used to develop a design guide to determine n values for heavily vegetated flood plains.

The estimation method can be used for determination of n for channels and vegetated flood plains. In this procedure, the value of n may be computed by first selecting a base value of n for natural materials making up the surface of the channel or flood plain and then increasing n for the various factors that affect the roughness of the channel or flood plain.

The vegetation-density method is applicable to wide, wooded flood plains. In this method, the vegetation density of a wooded flood plain is measured by determining the area occupied by the trees in a representative sample. Also necessary is selection of a base n for the natural surface material, an estimation of depth of flow, and selection of an effective-drag coefficient. After these parameters are determined, the n for the flood plain can be computed.

Two other methods that were evaluated are the roughness-concentration method and the regression-analysis method. Neither of these methods were used in the design guide. The roughness-concentration method is similar to the vegetation-density method. Both of these methods are based on the balance of the momentum equation. However, the vegetation-density method is more applicable for field determination of n values. Also, the regression-analysis method is not applicable for field determination of n values.

Data were collected at 10 sites, including 27 representative sample areas. All of the sites were wide, heavily wooded flood plains having an average slope of 6 ft/mi and an average width of 2,000 ft. The n values for the sites ranged from 0.08 to 0.18. As all sites were in heavily wooded flood plains, they were applicable to testing the vegetation-density method of determining n values.

Computation of n values for wooded flood plains, using the vegetation-density method, yielded good results. A comparison of computed n versus verified n gives a standard error of 0.92. The vegetation-density method is easy to use. A representative sample area (100 ft by 50 ft) is selected along the cross section. The number of trees and their diameter are measured in the sample area to determine the vegetation density. Once the vegetation density is measured and the other parameters determined, the n value can be computed.

One problem lies in the selection of an effective drag coefficient. Experimental flume data indicate that an effective-drag coefficient for flood plains ranges from about 1.0 to 2.0. Field data for densely wooded flood plains indicates that the effective-drag coefficient seems to be a magnitude higher than the flume data, in the range of 10 to 20, depending on the depth of flow. One explanation for this difference is that the depth of flow for the field data (2.0 to 5.0 ft) is much larger than for the flume data (0.296 to 1.169 ft). Also, the vegetation density for the flume data had a range of 2.316 to 0.231; this is much larger than the vegetation density for the field data, which has a range of 0.0130 to 0.0054. Both field and laboratory flume data show that the effective-drag coefficient decreases as hydraulic radius increases. More field data are needed to aid in determining better values of effective-drag coefficients. However, using the effective-drag coefficients from the available field data yields good results.

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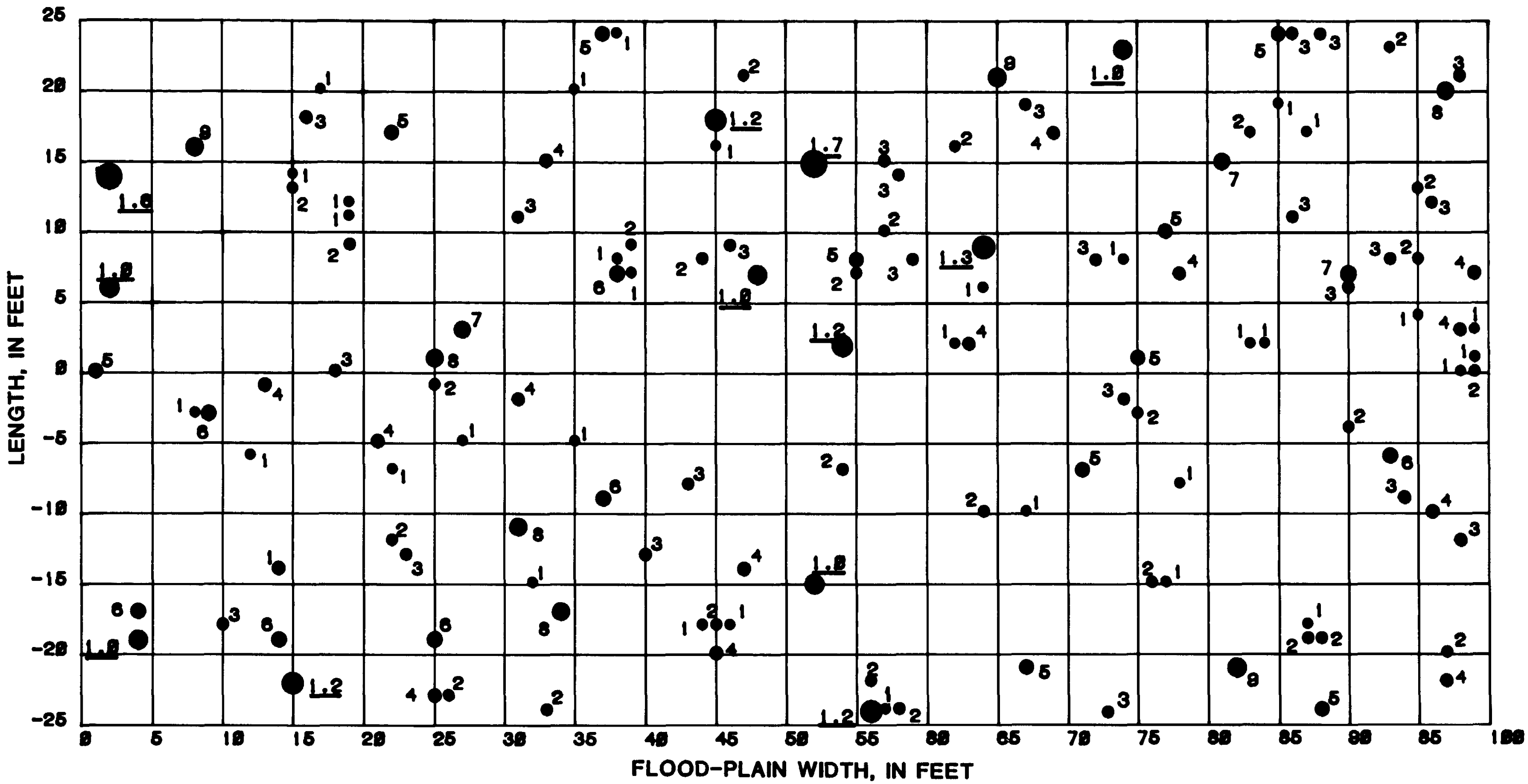
HYDROLOGIC DATA

page 37 follows

SITE: Pea Creek, cross section 4

DATE: March 13, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 50 feet tall, including some fallen trees, and a few vines and light ground cover. The surface is irregular with some sloughs.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

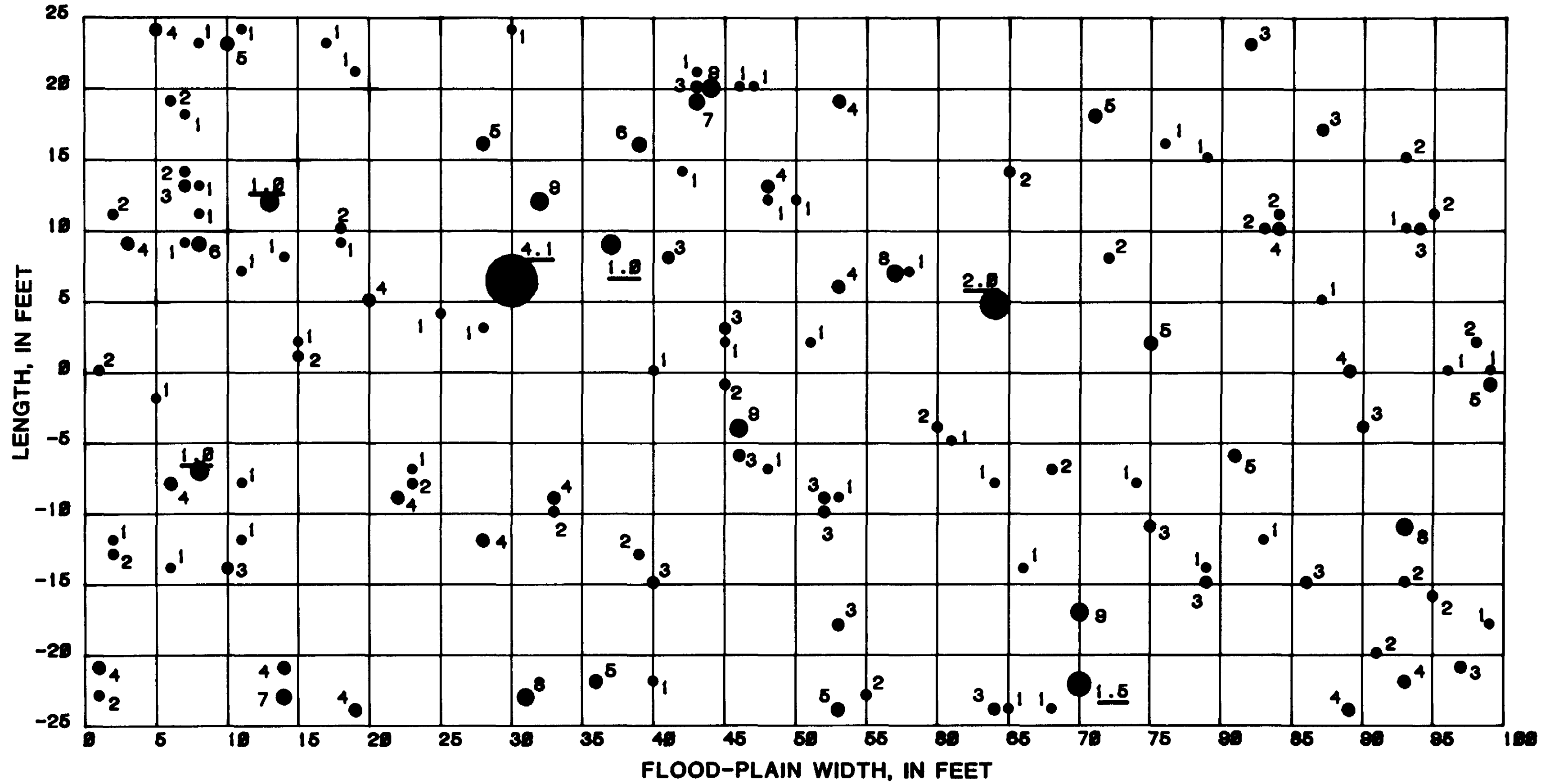
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 8.

SITE: Pea Creek, cross section 5

DATE: March 13, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 30 feet tall, including some fallen trees, and very little ground cover. The surface is fairly smooth with some rises.



EXPLANATION

● 2 Location of tree; number indicates tree diameter in tenths of a foot

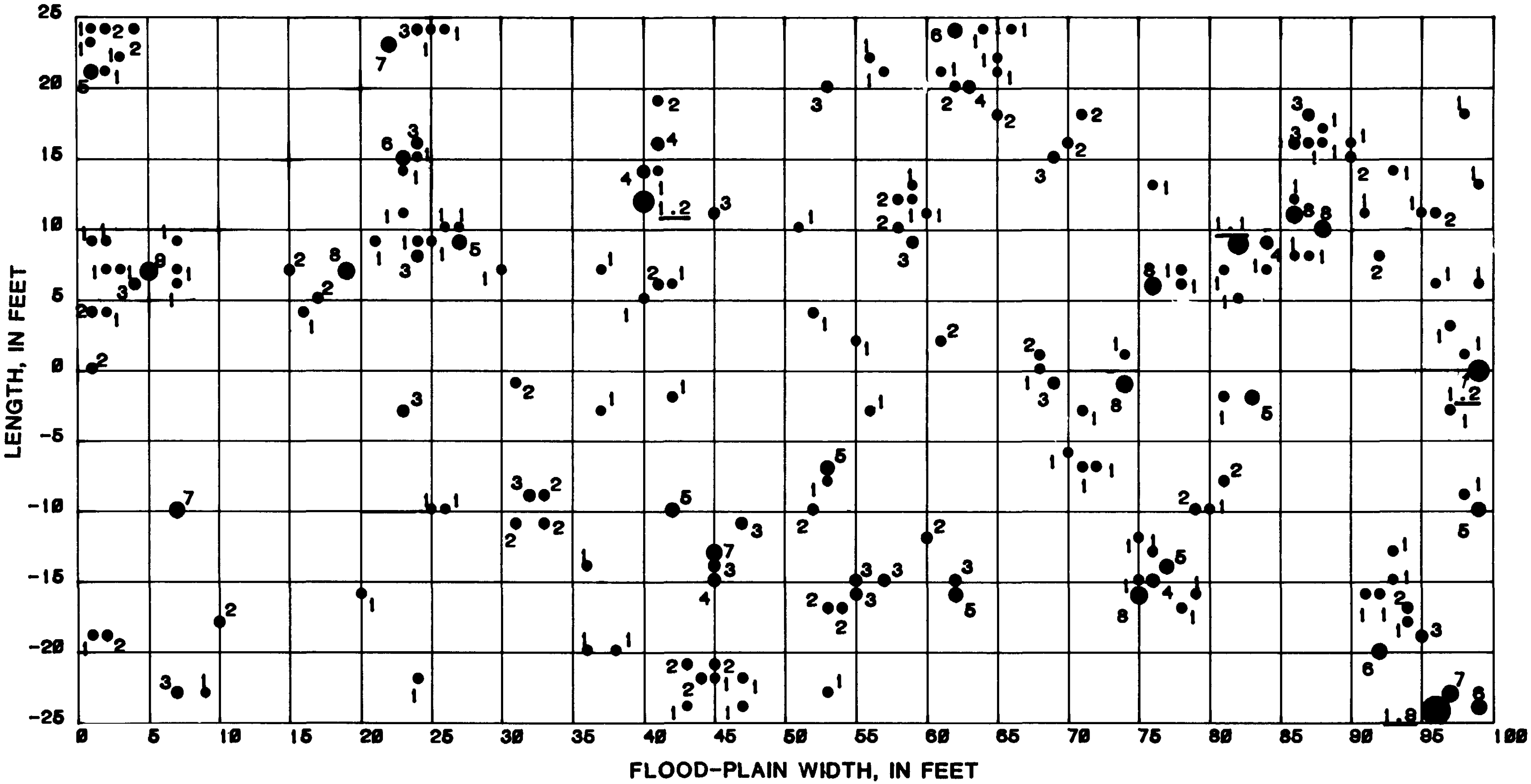
● 1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 9.

SITE: Yellow River, cross section 2

DATE: March 15, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 30 feet tall, many large vines in trees and on the ground, and very little ground cover. The surface is fairly smooth except for some low rises.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

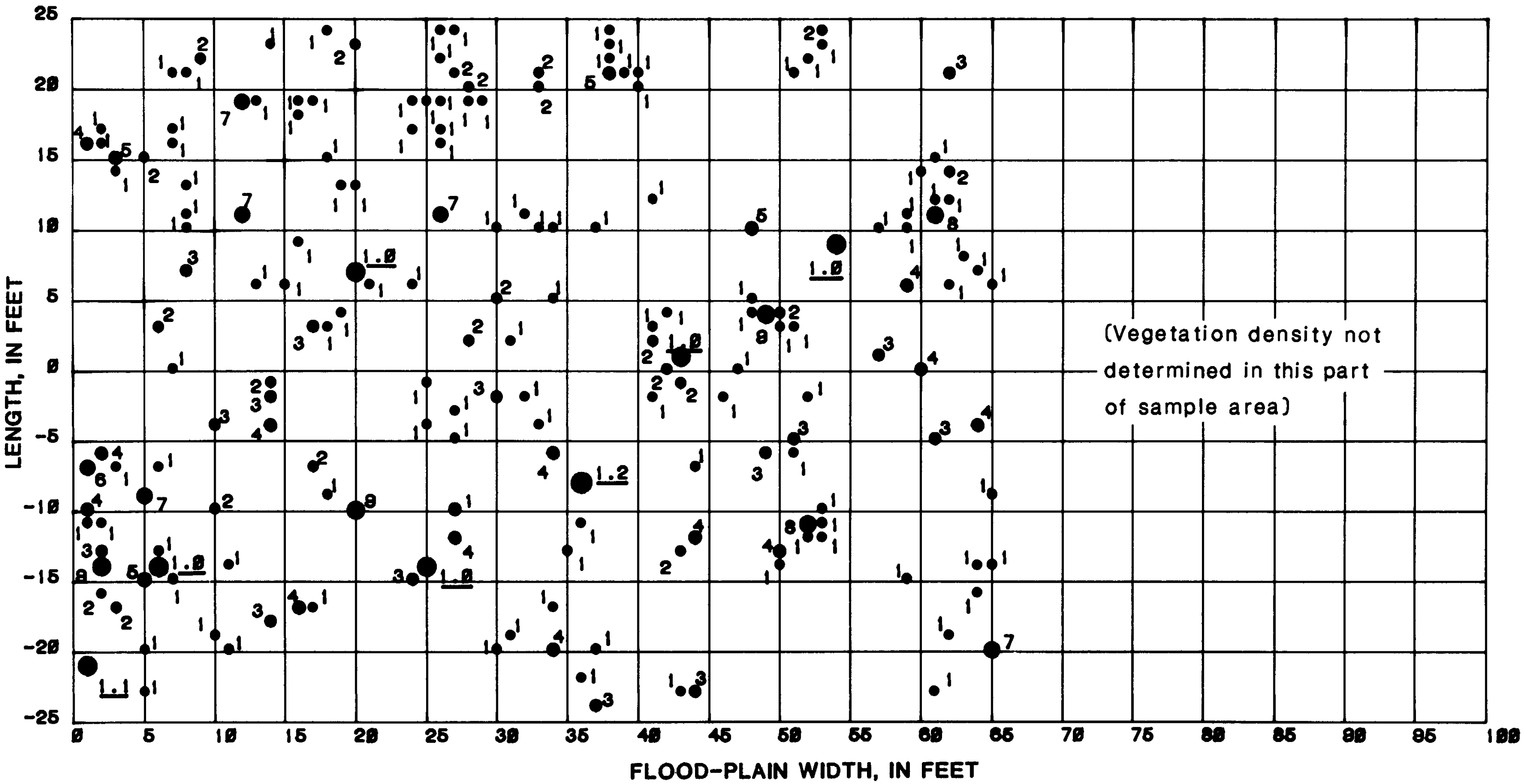
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 10.

SITE: Yellow River, cross section 12

DATE: March 15, 1979

DESCRIPTION: Flood plain consists of hardwood trees, many vines and briars, and some ground cover. The surface is fairly smooth.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

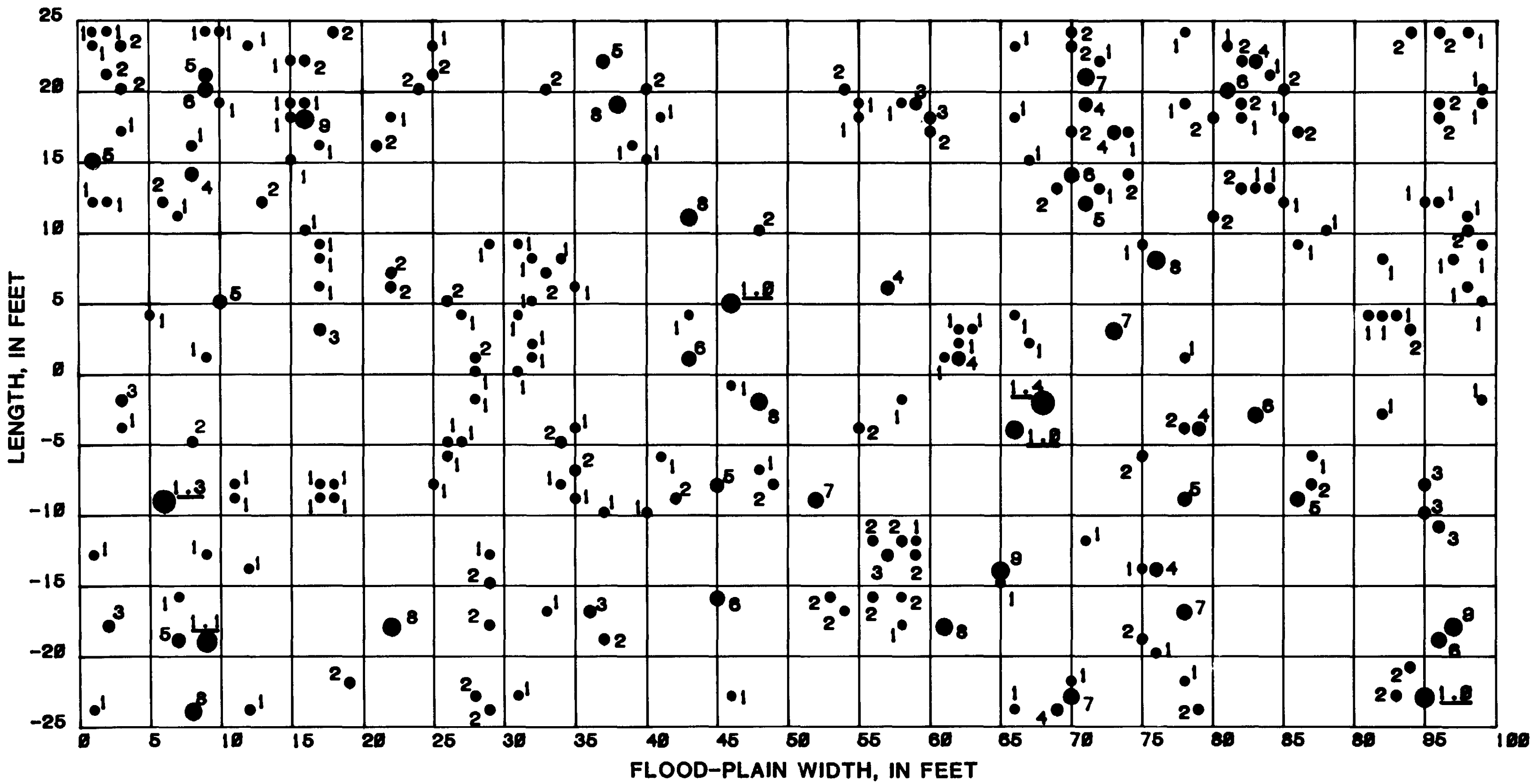
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 11.

SITE: Poley Creek, cross section 2

DATE: March 14, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 40 feet tall, including many small-diameter trees, and some vines and ground cover. The surface is fairly smooth with a firm soil base.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

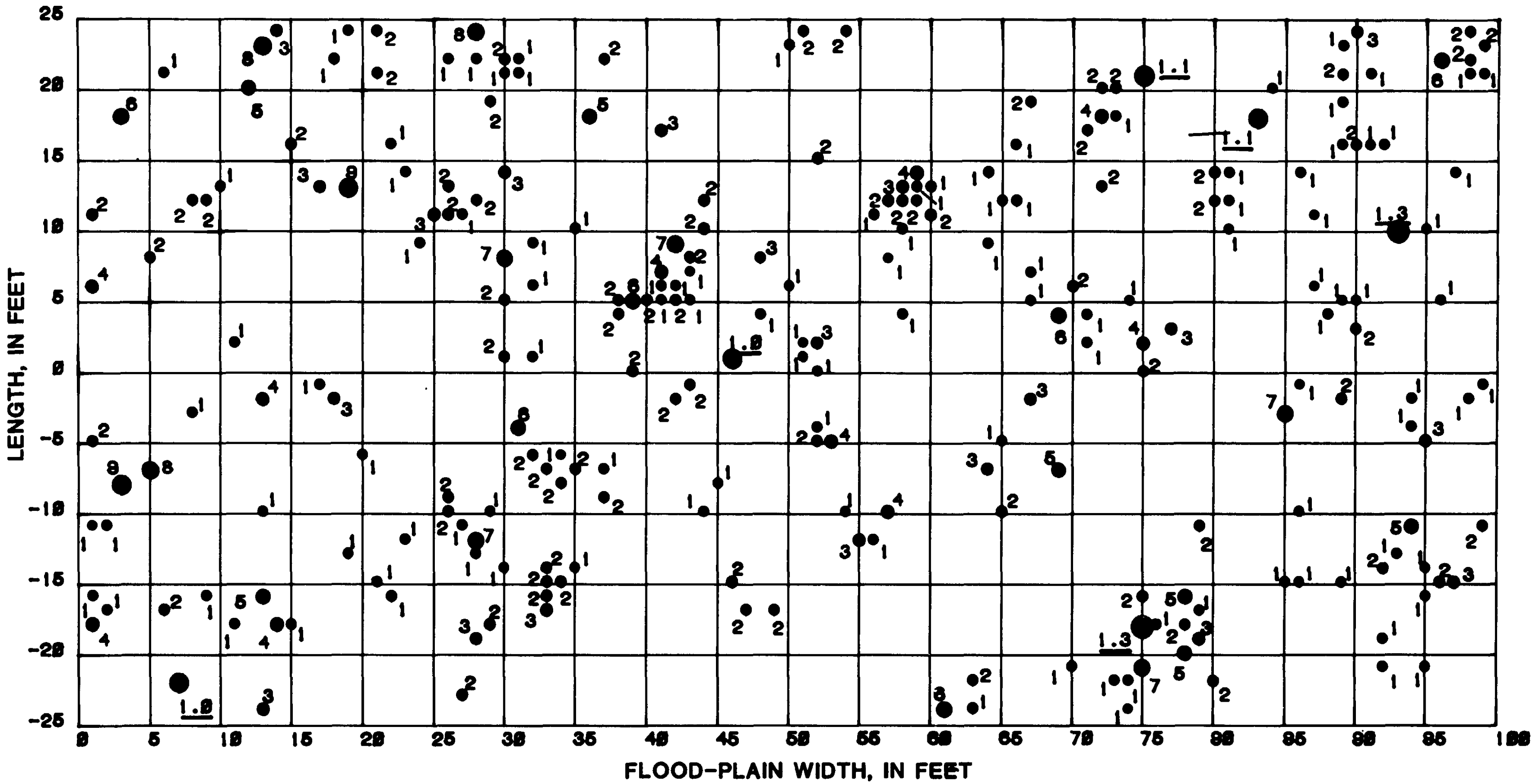
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 12.

SITE: Poley Creek, cross section 3

DATE: March 14, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 30 feet tall, including many small-diameter trees, and some ground cover. The surface is slightly irregular with some sloughs.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

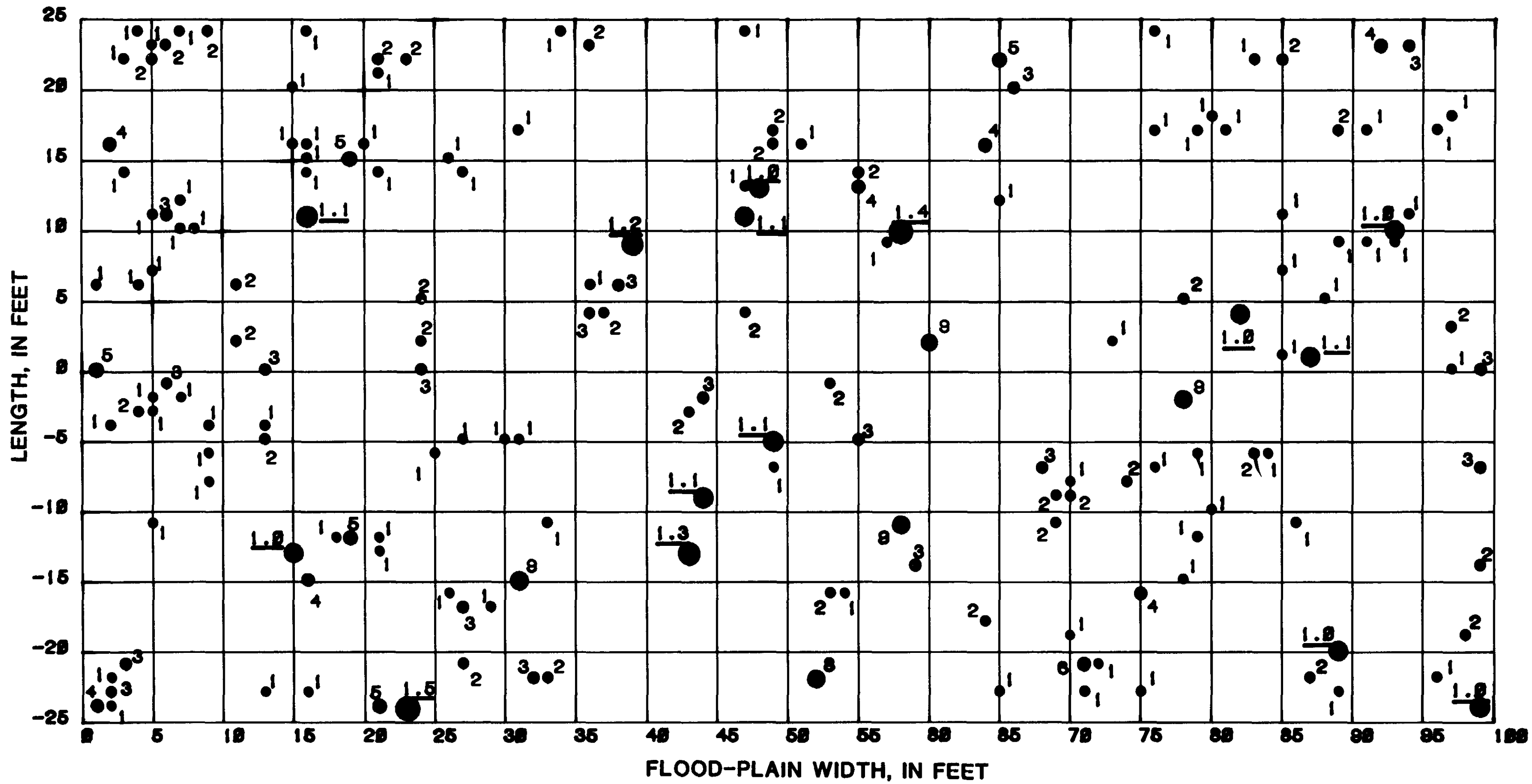
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 13.

SITE: Poley Creek, cross section 4

DATE: March 14, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 40 feet tall, including many large-diameter trees. The surface is fairly smooth with some low rises.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

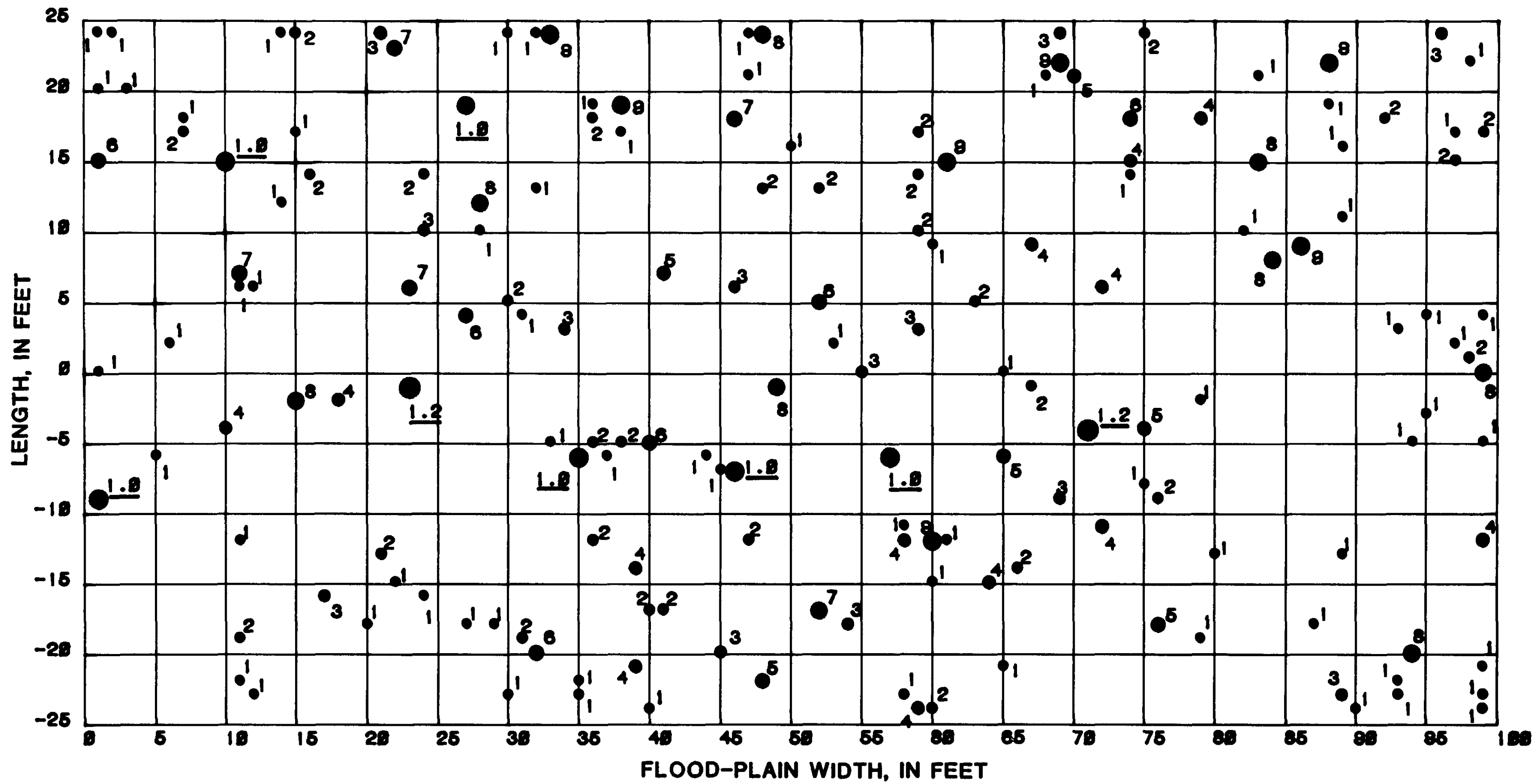
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 14.

SITE: Poley Creek, cross section 5

DATE: March 14, 1979

DESCRIPTION: Flood plain consists of mostly hardwood trees up to 50 feet tall, including many large-diameter trees, and very little ground cover. The surface is fairly smooth.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

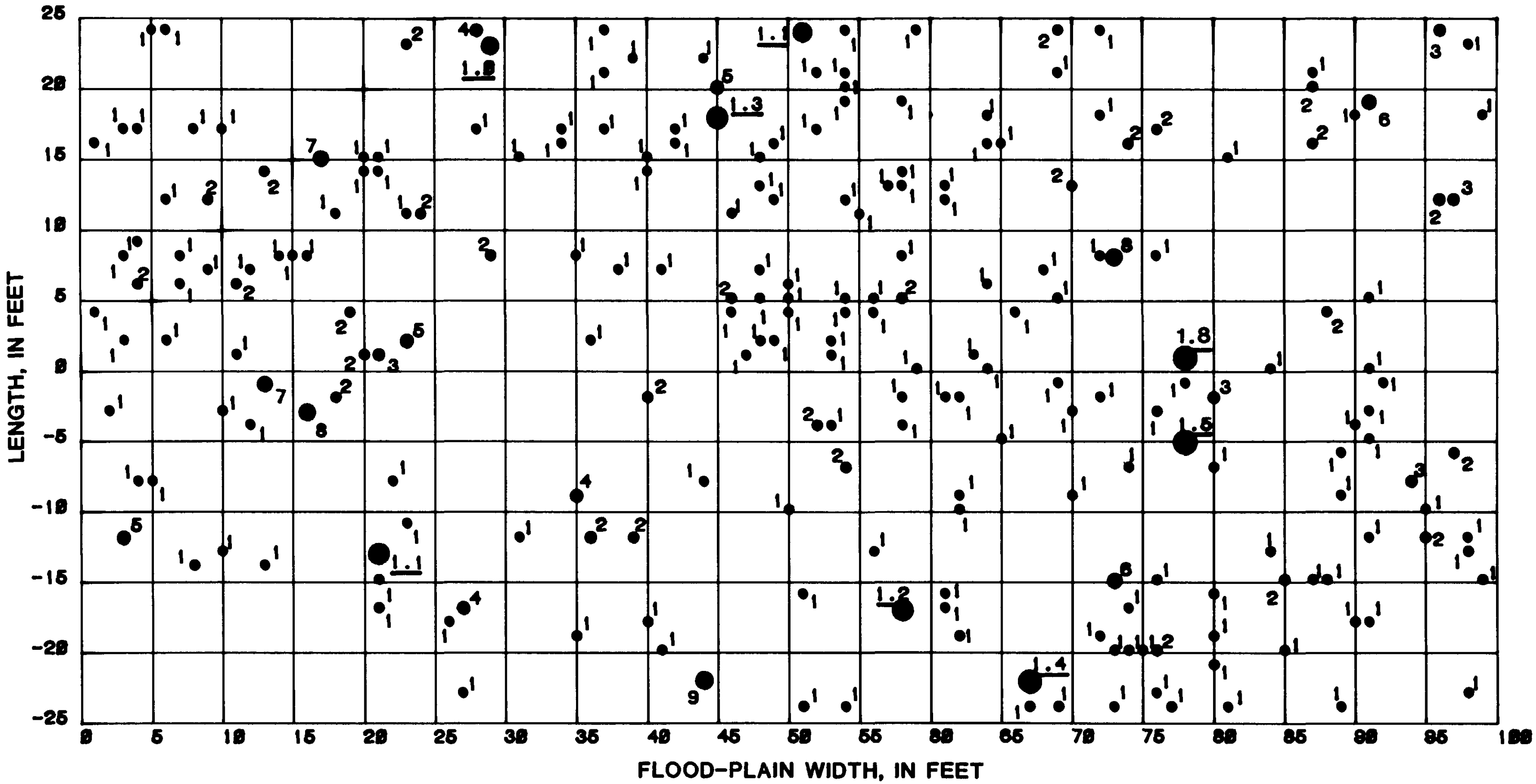
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 15.

SITE: Yockanookany River, cross section 300

DATE: March 28, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 50 feet tall, including many small-diameter trees, and very little ground cover. The surface is fairly smooth.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

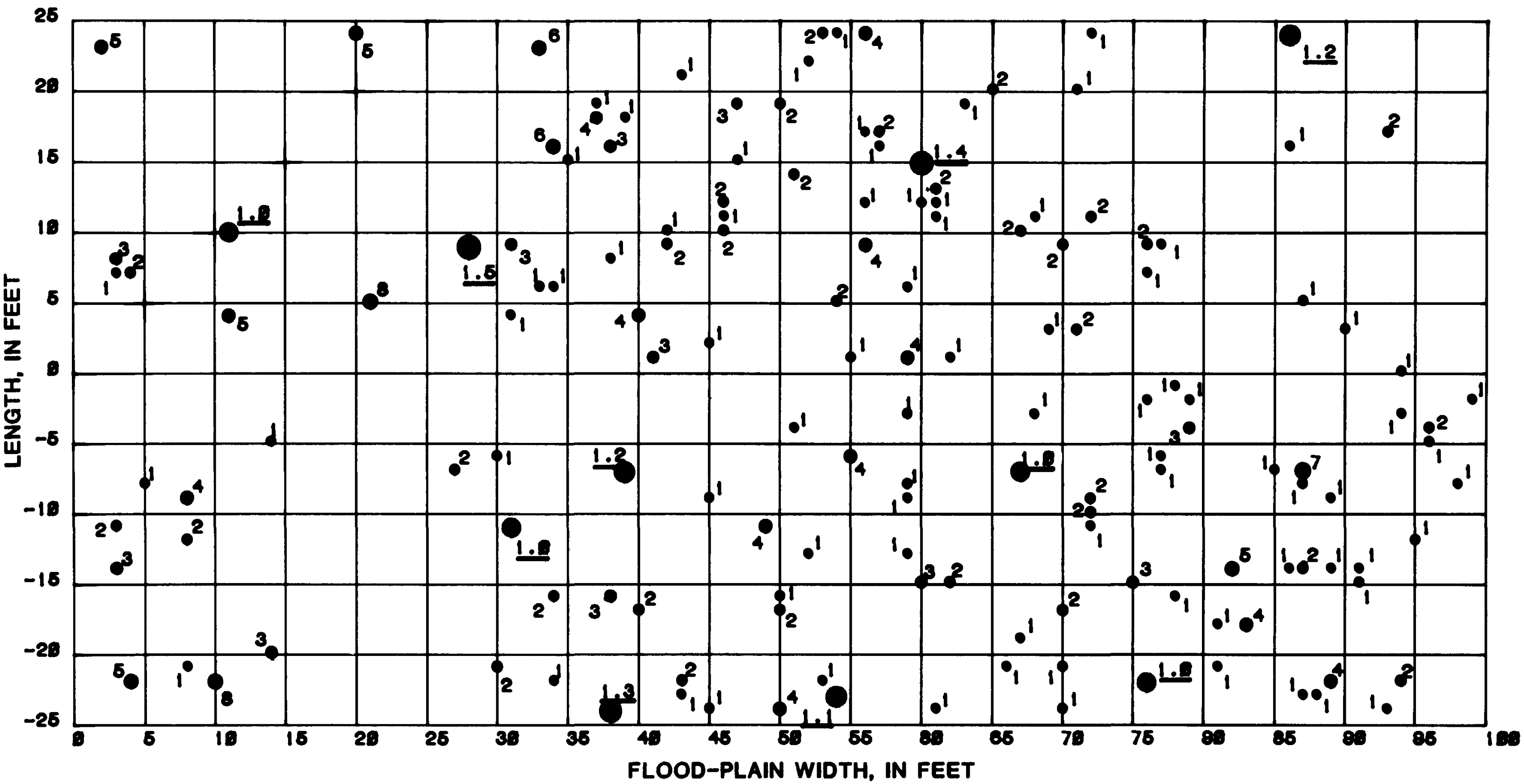
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 16.

SITE: Yockanookany River, cross section 400

DATE: March 28, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 50 feet tall, including many small-diameter trees, and very little ground cover. The surface is fairly smooth.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

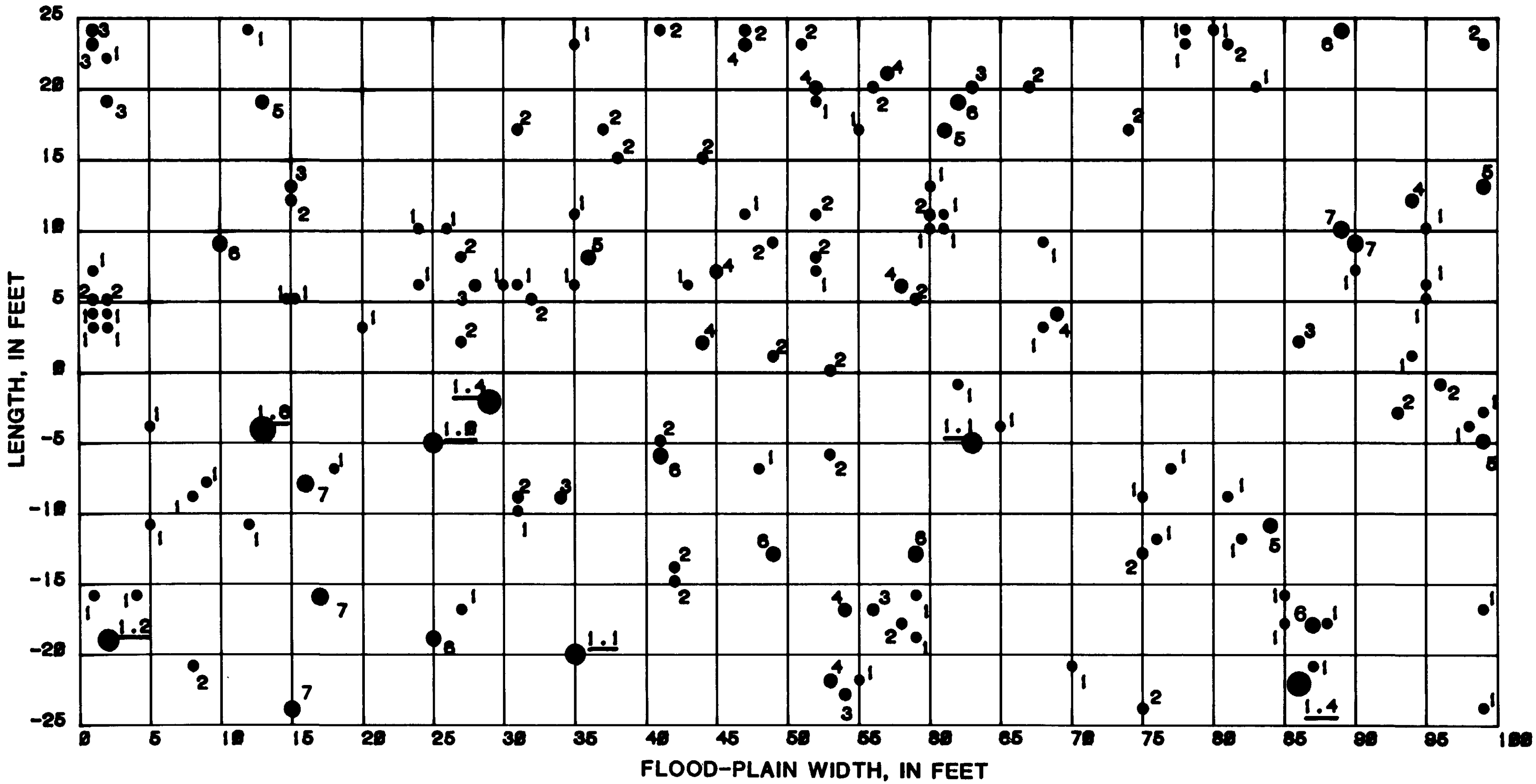
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 17.

SITE: Yockanookany River, cross section 500

DATE: March 28, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 40 feet tall, including many small-diameter trees, and very little ground cover. The surface is fairly smooth.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

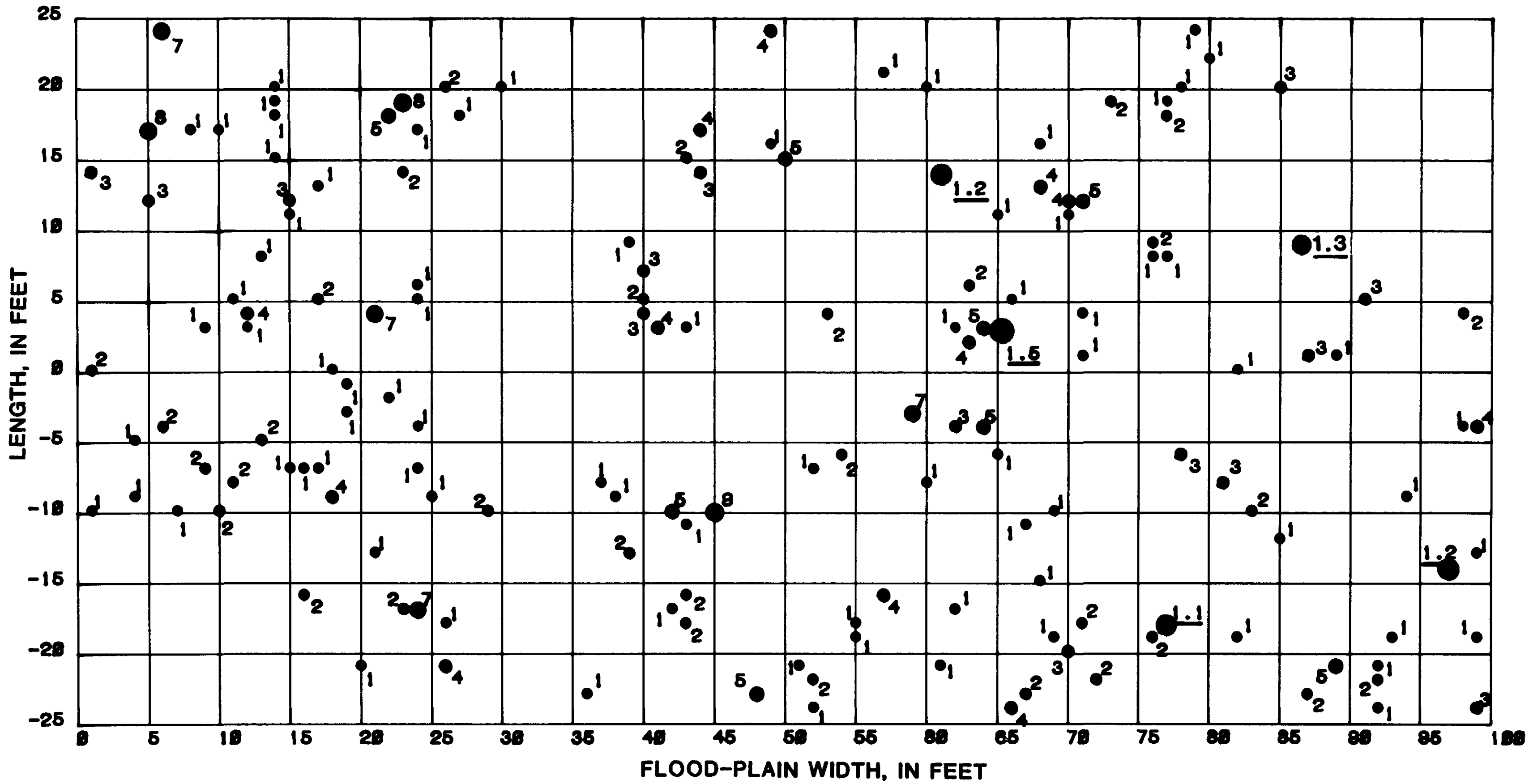
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 18.

SITE: Coldwater River, cross section 2, sample area 1

DATE: April 5, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 40 feet tall, with some vines, and very little ground cover. The surface is slightly irregular with some low rises.



EXPLANATION

•2 Location of tree; number indicates tree diameter in tenths of a foot

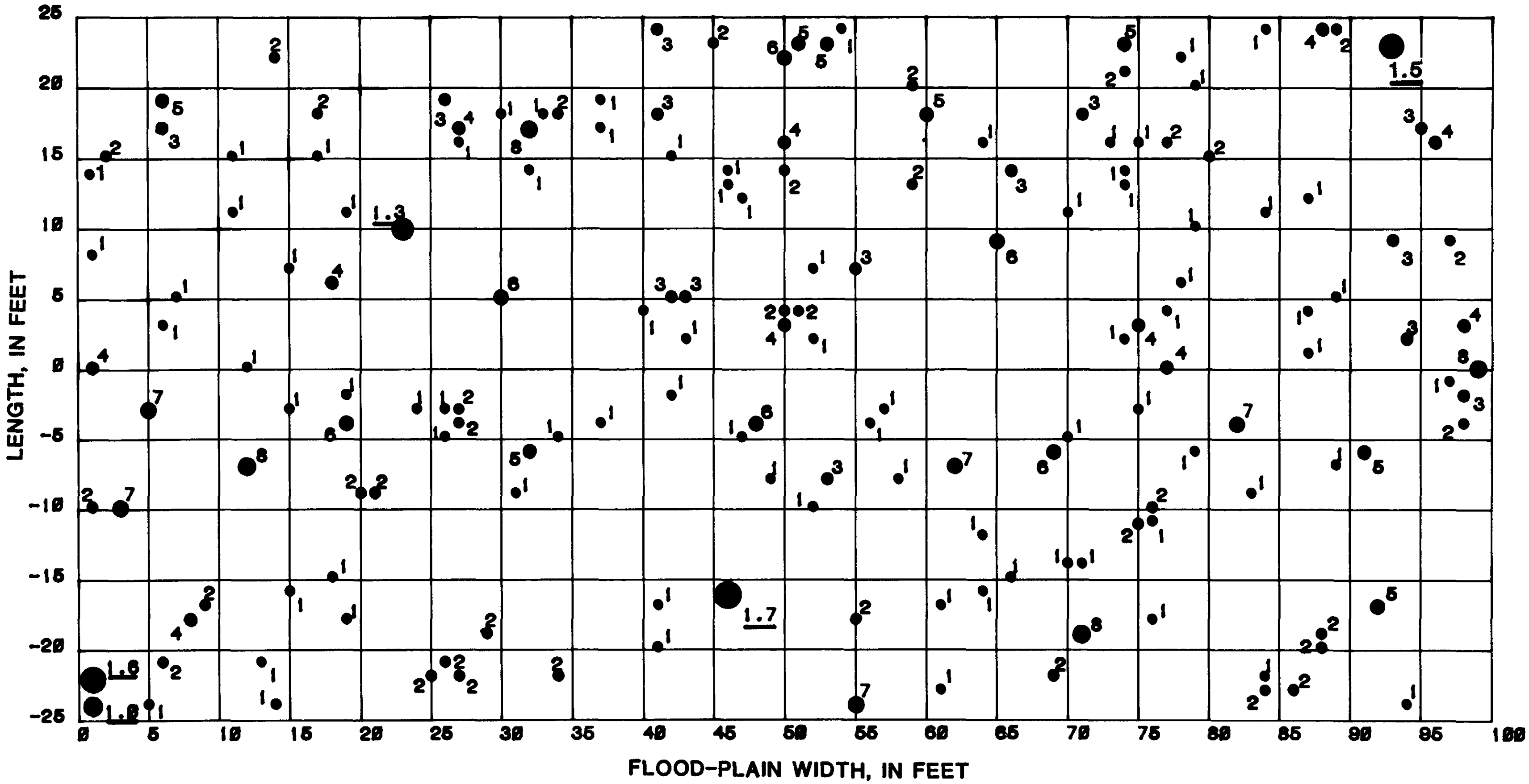
● 1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 19.

SITE: Coldwater River, cross section 2, sample area 2

DATE: APRIL 5, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 40 feet tall, including many large-diameter trees, and very little ground cover. The surface is fairly smooth.



EXPLANATION

• 2 Location of tree; number indicates tree diameter in tenths of a foot

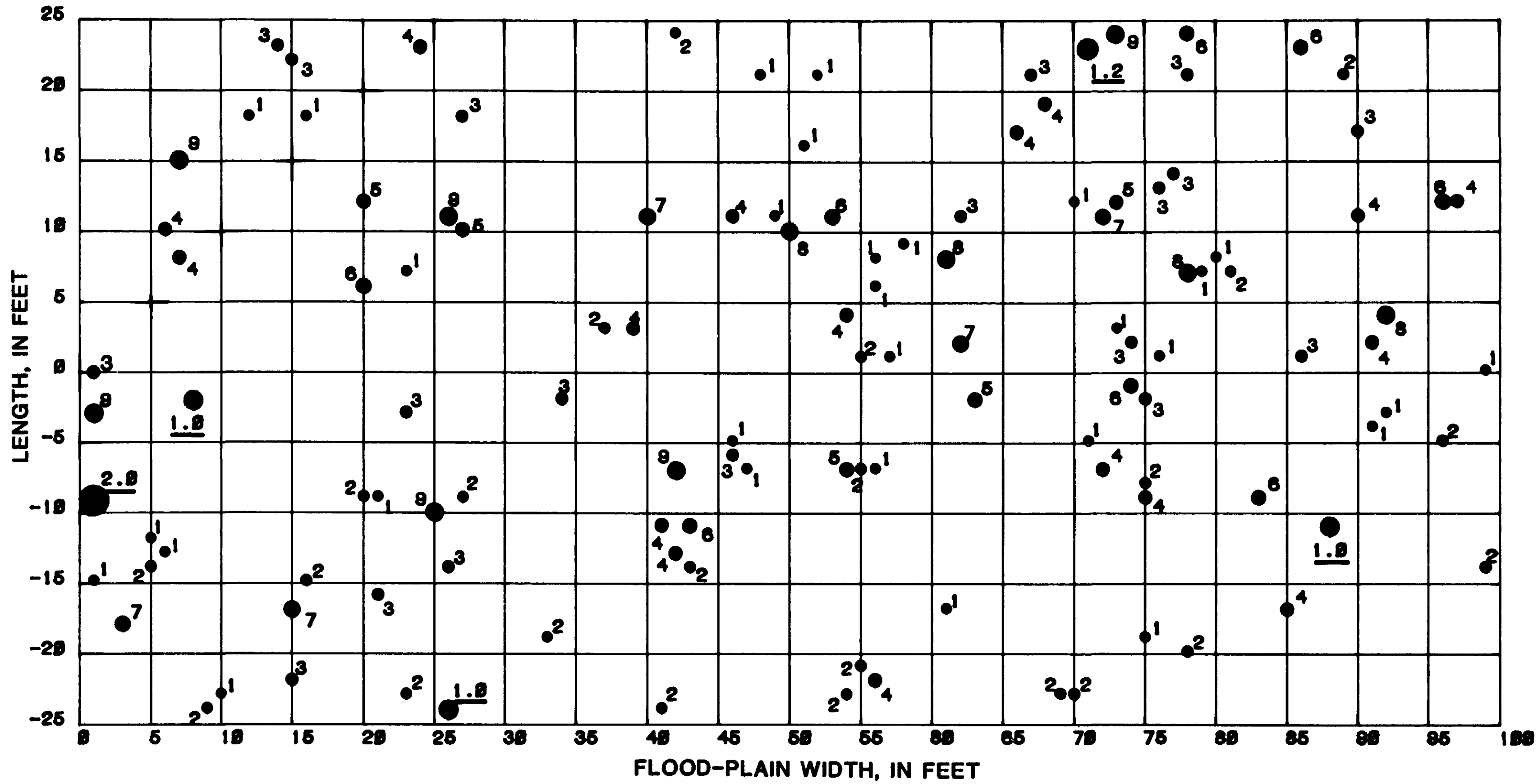
● 1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 20.

SITE: Coldwater River, cross section 2, sample area 3

DATE: April 5, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 50 feet tall, including many large-diameter trees, and very little ground cover. The surface is slightly irregular with some low rises.



EXPLANATION

• 2 Location of tree; number indicates tree diameter in tenths of a foot

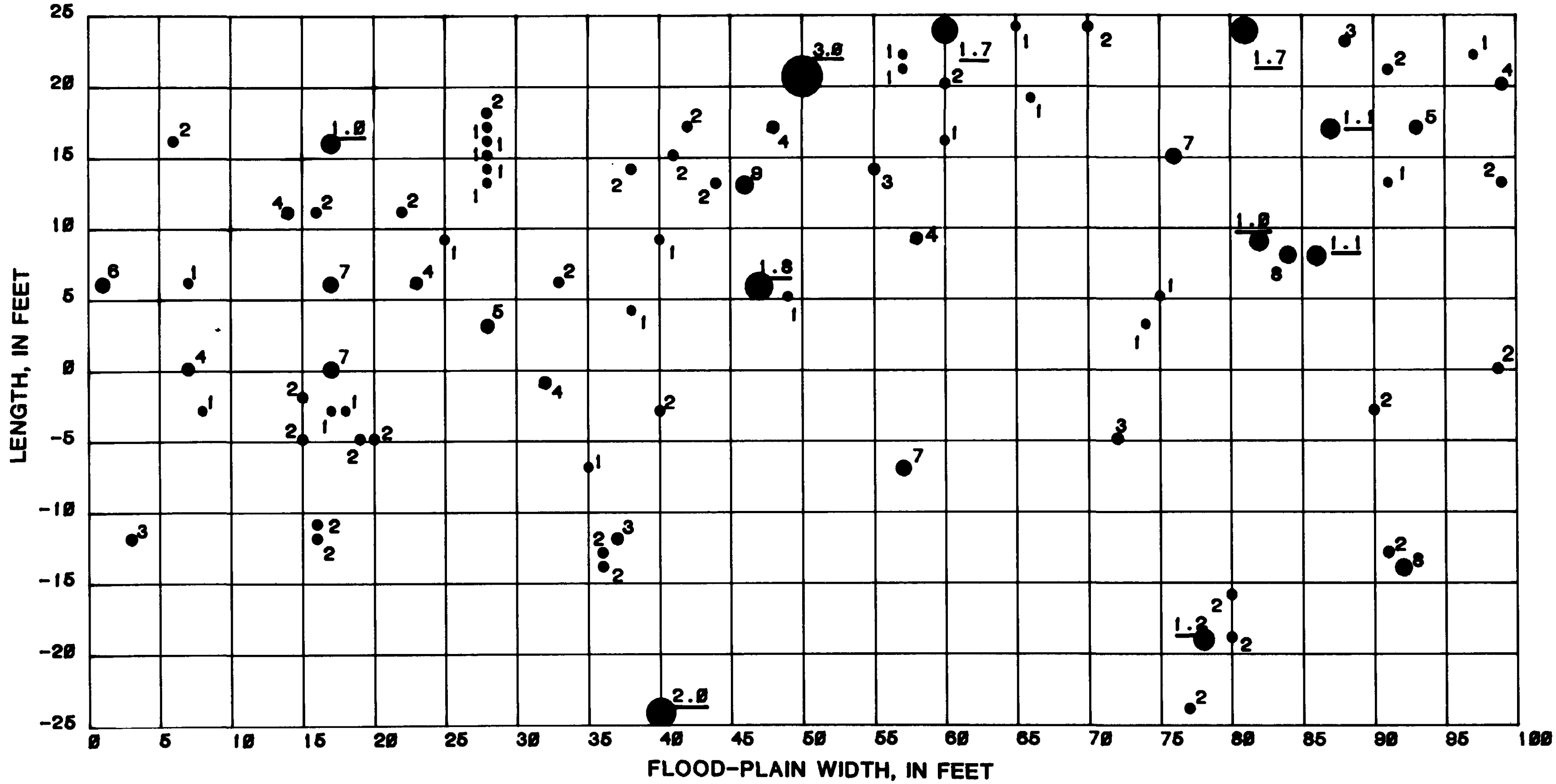
● 1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 21.

SITE: Bayou de Loutre, cross section 200

DATE: February 14, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 50 feet tall, including many large-diameter trees, and no ground cover. The surface is slightly irregular.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

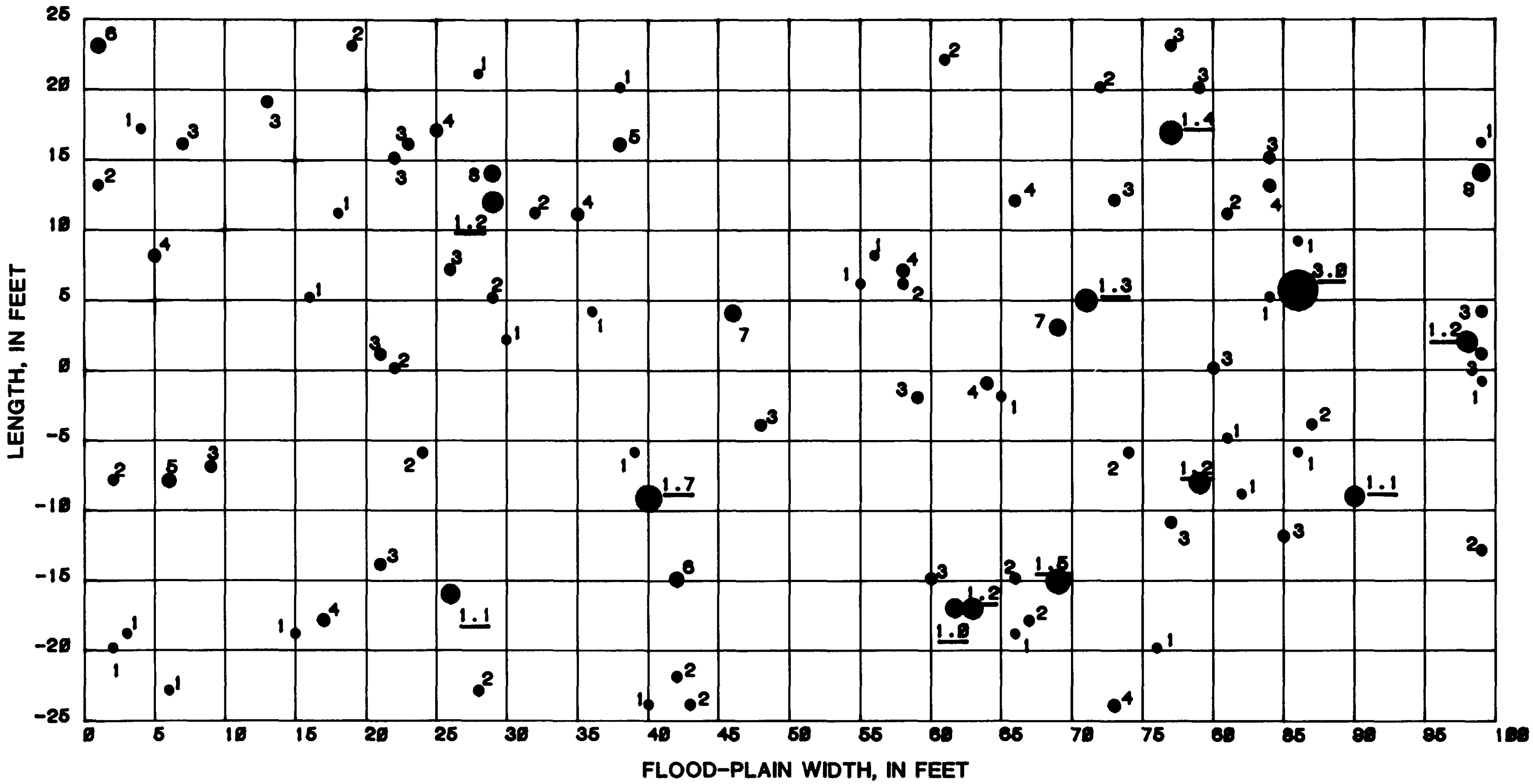
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 22.

SITE: Bayou de Loutre, cross section 300, sample area 1

DATE: February 14, 1979

DESCRIPTION: Flood plain consists of hardwood trees, including many large-diameter trees, and no ground cover. The surface is irregular with some sloughs.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

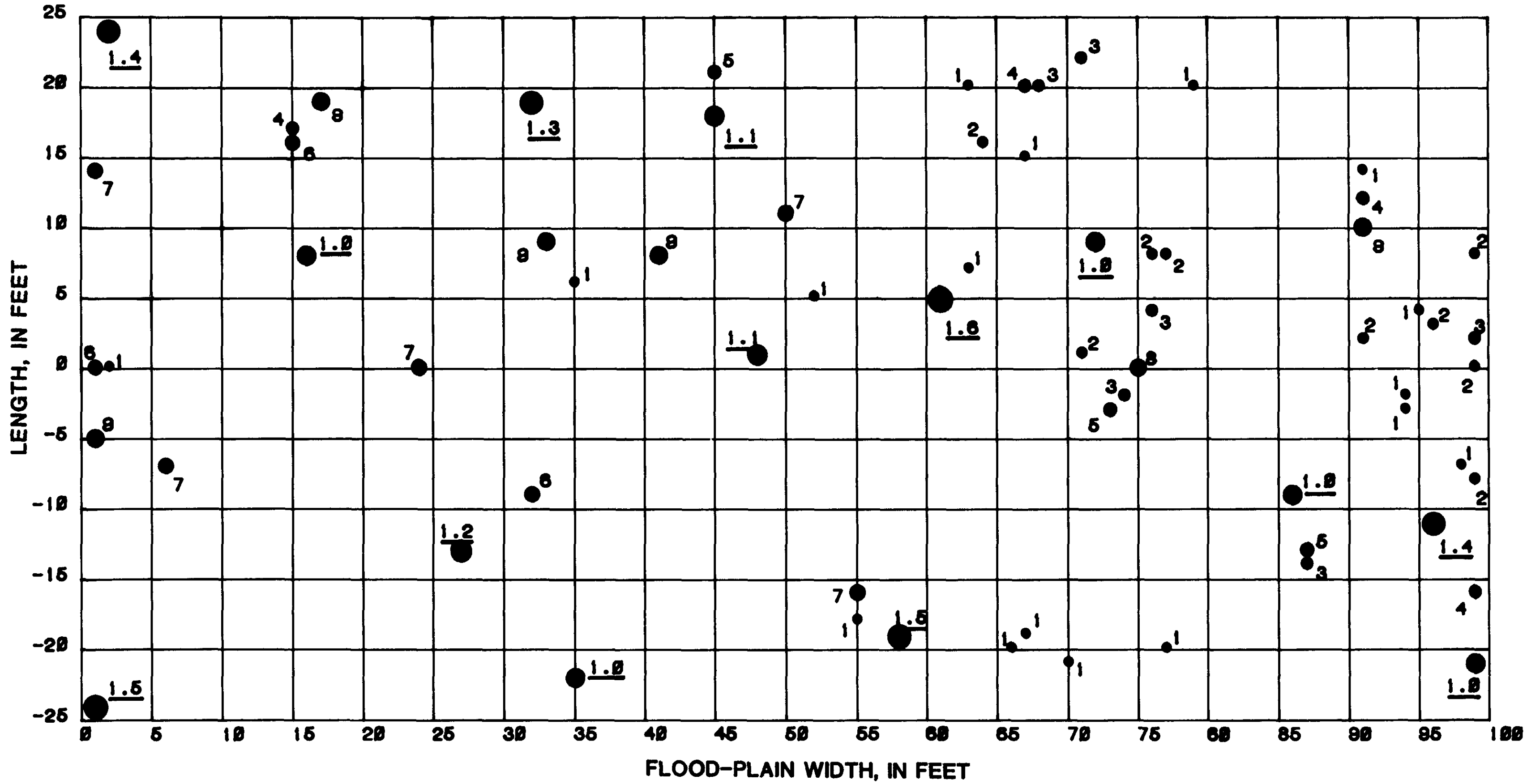
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 23.

SITE: Bayou de Loutre, cross section 300, sample area 2

DATE: February 14, 1979

DESCRIPTION: Flood plain consists of hardwoods up to 50 feet tall, including many large-diameter trees, and no ground cover. The surface is irregular with some sloughs.



EXPLANATION

• 2 Location of tree; number indicates tree diameter in tenths of a foot

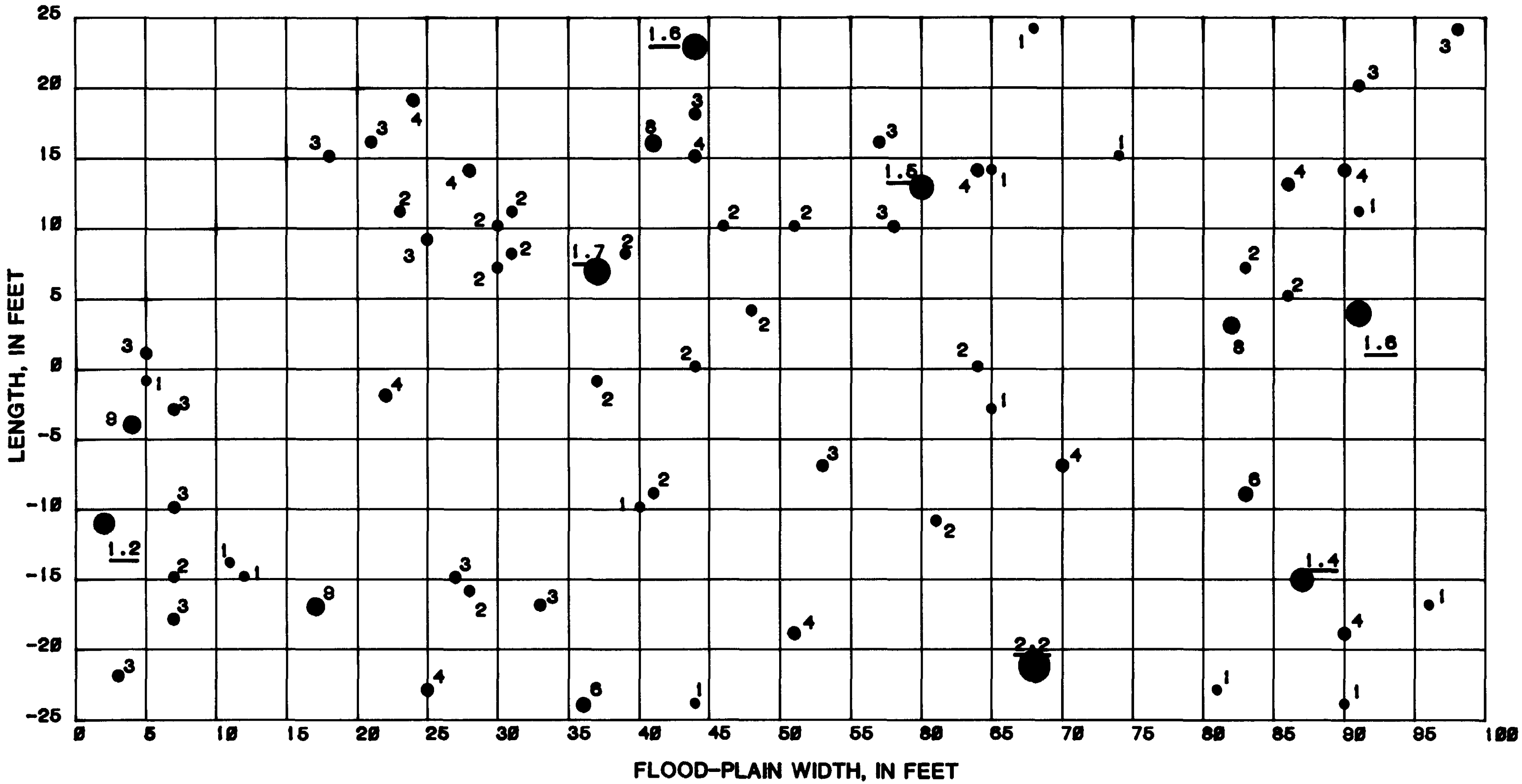
● 1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 24.

SITE: Bayou de Loutre, cross section 400

DATE: February 14, 1979

DESCRIPTION: Flood plain consists of hardwood trees, including many large-diameter trees, and no ground cover. The surface is slightly irregular with some sloughs.



EXPLANATION

• 2 Location of tree; number indicates tree diameter in tenths of a foot

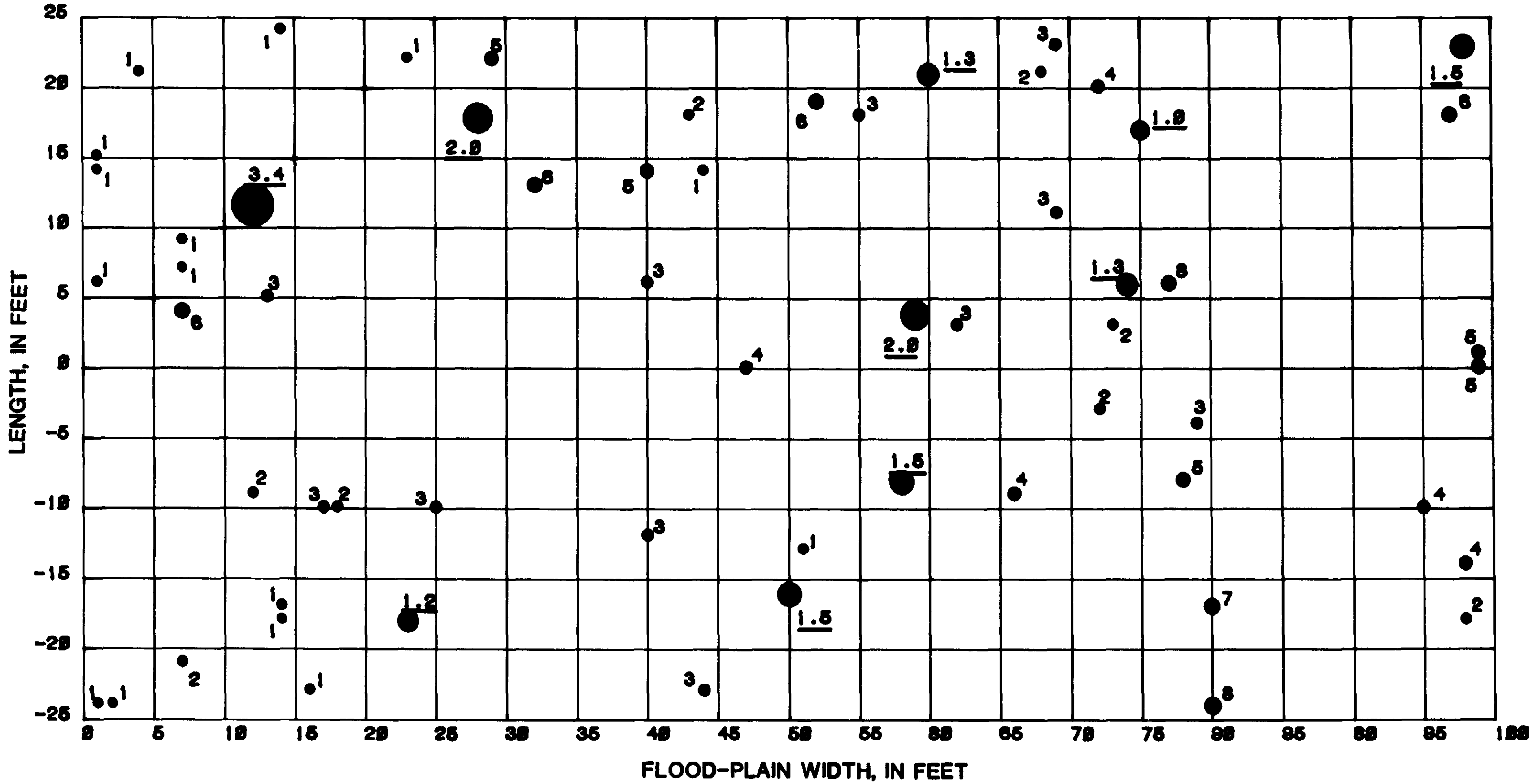
● 1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 25.

SITE: Bayou de Loutre, cross section 600

DATE: February 14, 1979

DESCRIPTION: Flood plain consists of mostly hardwood trees and very little ground cover. The surface is fairly smooth.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

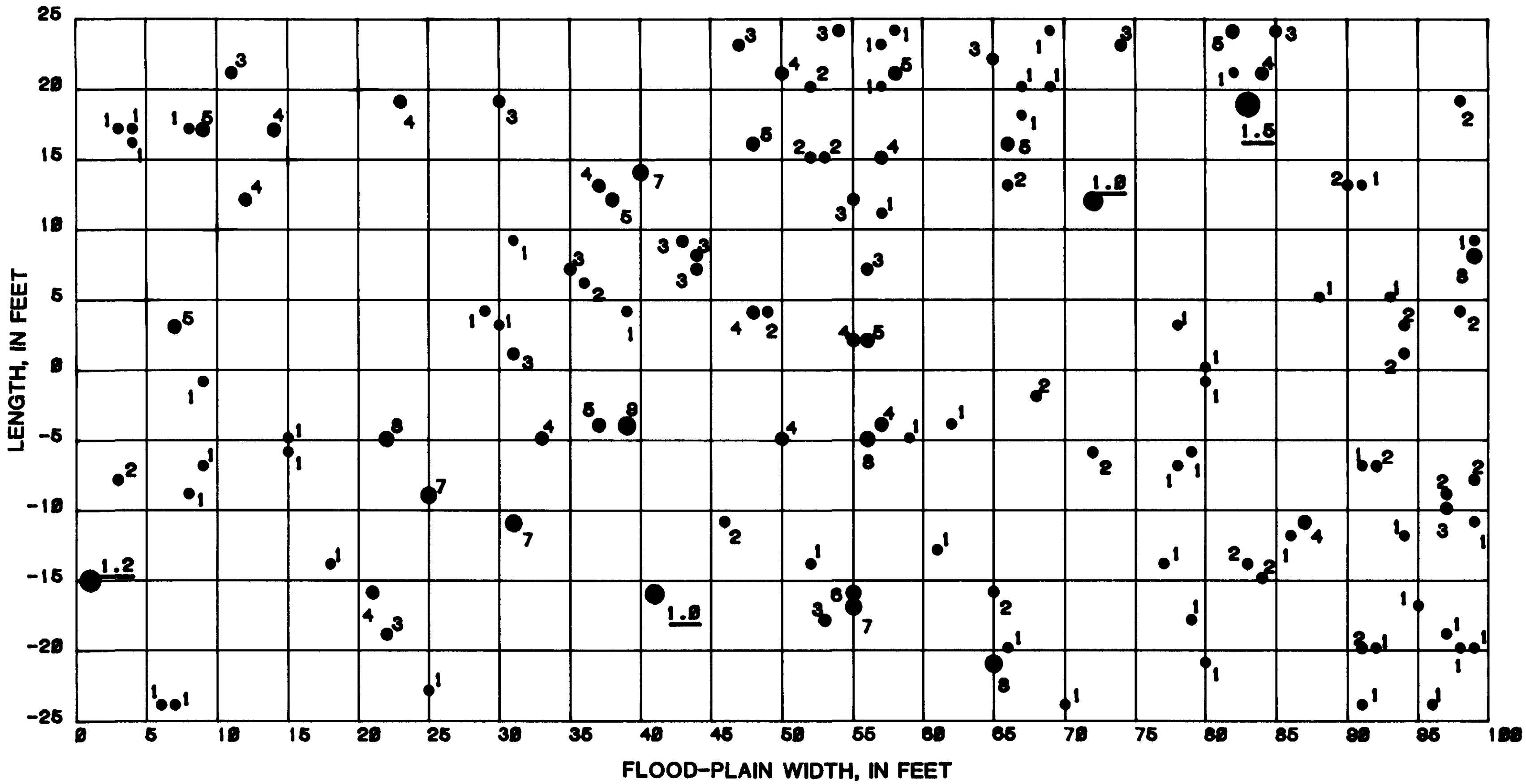
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 26.

SITE: Cypress Creek, cross section 300

DATE: February 13, 1979

DESCRIPTION: Flood plain consists of mostly hardwood trees, including many small-diameter trees, and a few vines and light ground cover. The surface is fairly smooth.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

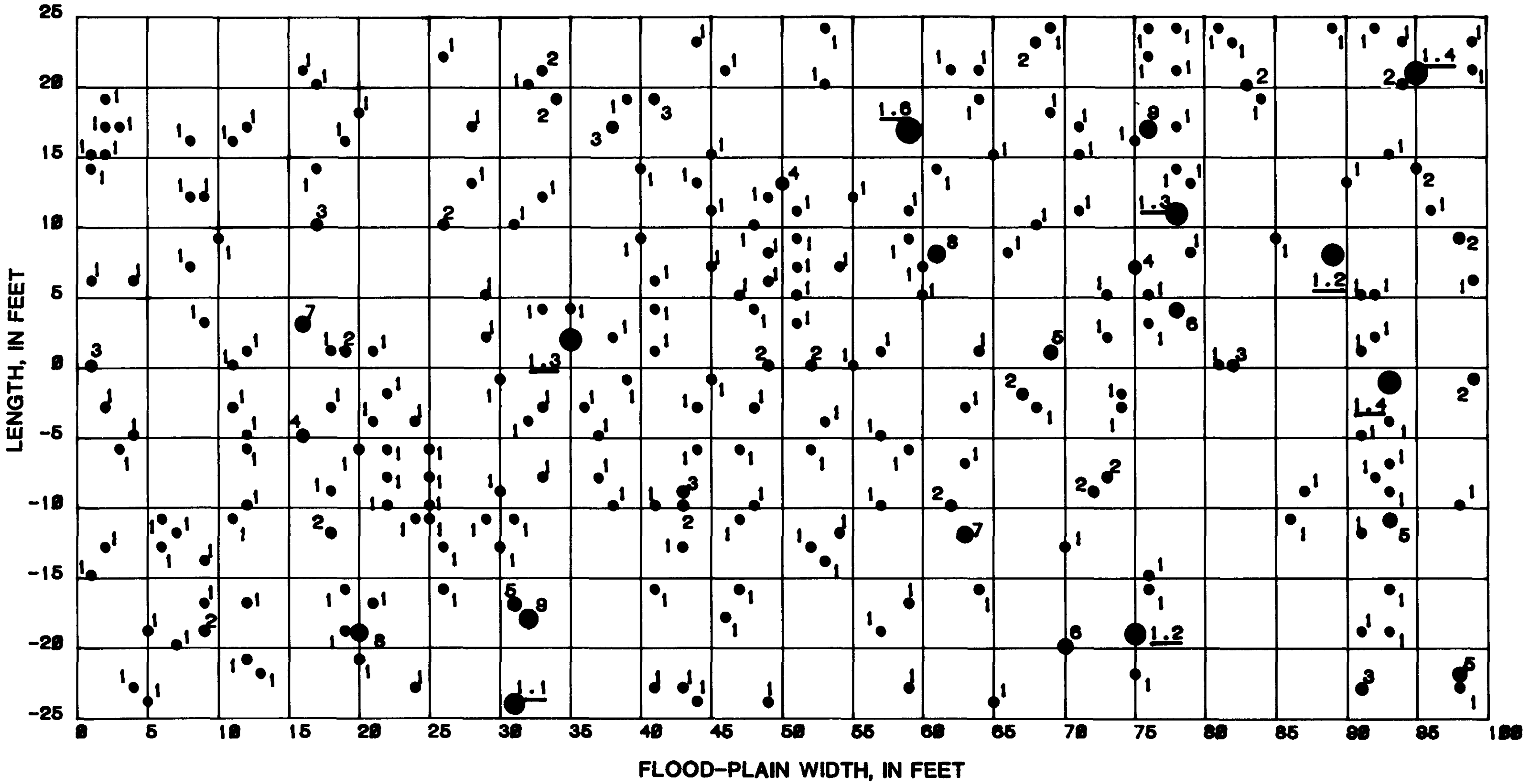
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 27.

SITE: Flagon Bayou, cross section 200

DATE: April 10, 1979

DESCRIPTION: Flood plain consists of many small-diameter trees, and no vines or ground cover. The surface is very irregular.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 28.

SITE: Flagon Bayou, cross section 300

DATE: April 10, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 50 feet tall, including many small-diameter trees, and very little ground cover. The surface is very irregular.

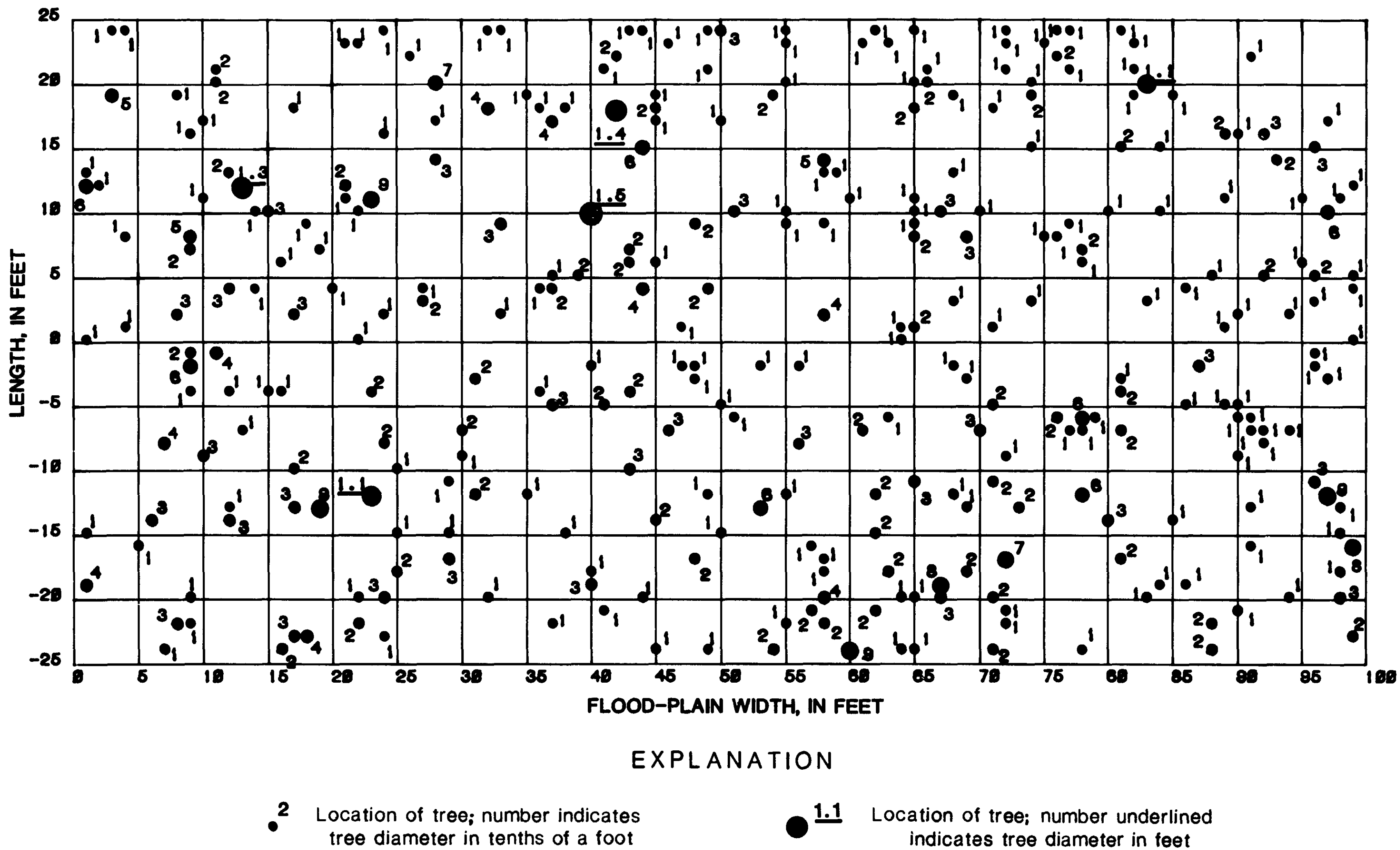
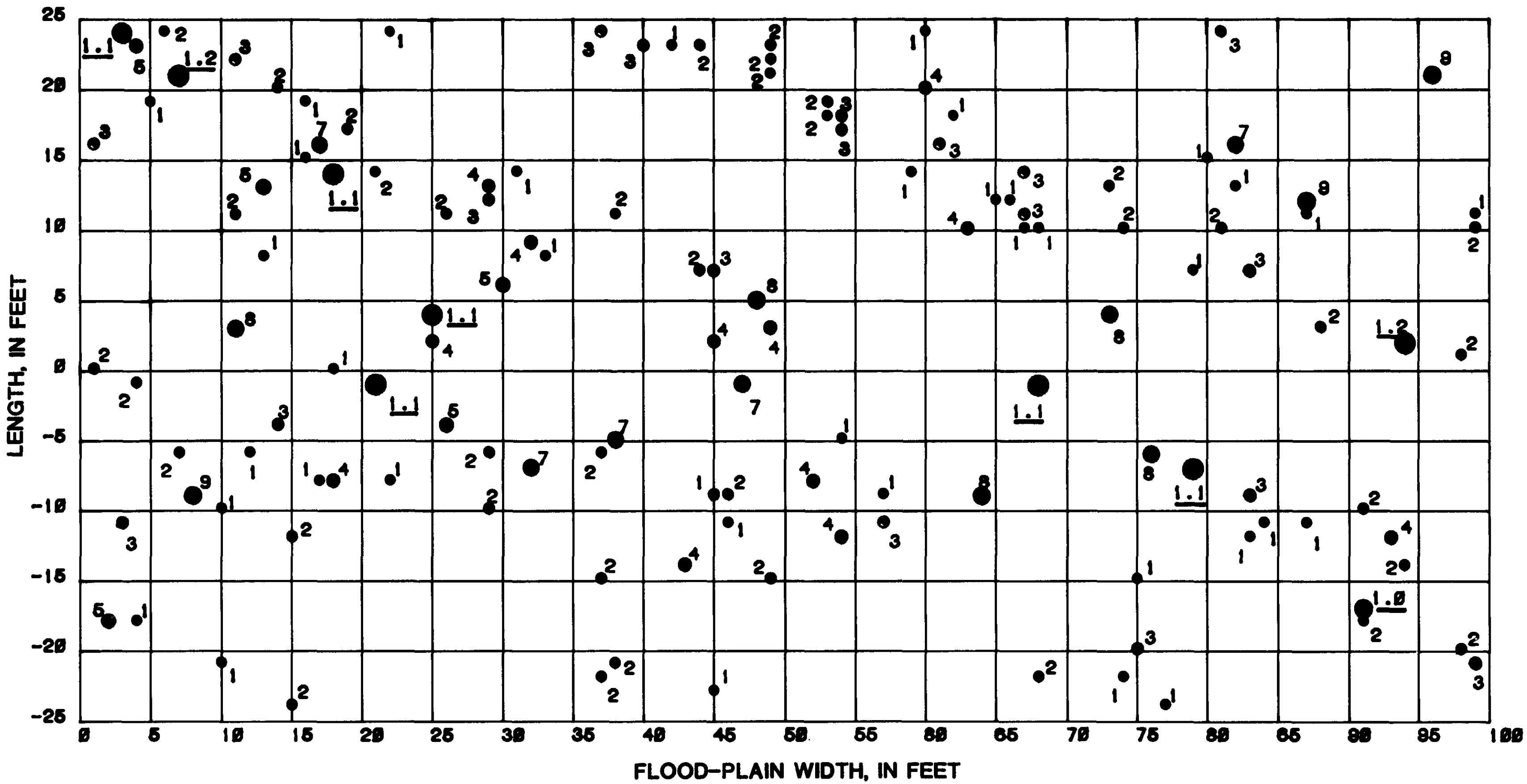


Figure 29.

SITE: Flagon Bayou, cross section 400

DATE: April 10, 1979

DESCRIPTION: Flood plain consists of hardwood trees up to 60 feet tall, including many large-diameter trees, and no ground cover. The surface is irregular with 2 foot rises.



EXPLANATION

• 2 Location of tree; number indicates tree diameter in tenths of a foot

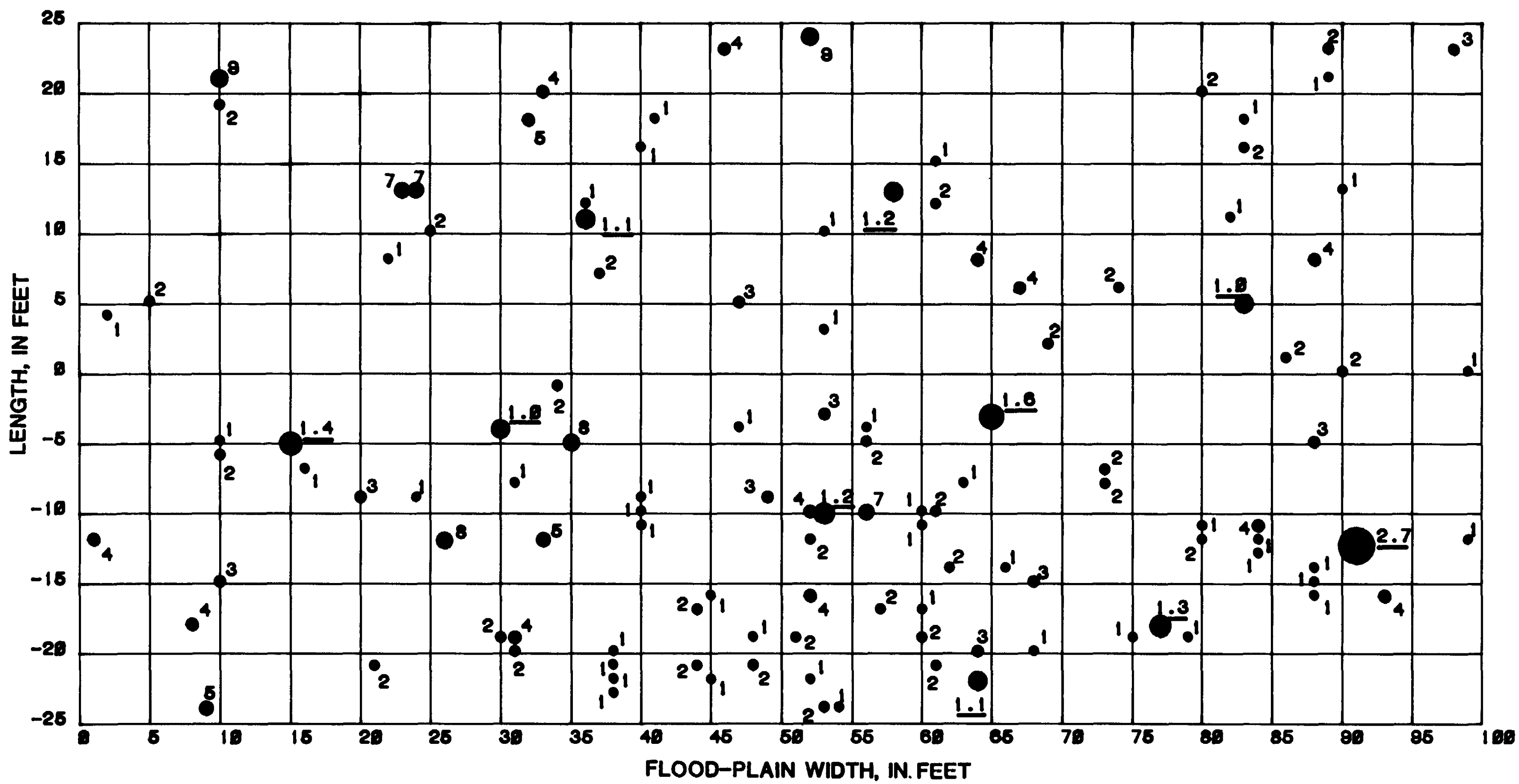
● 1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 30.

SITE: Alexander Creek, cross section 100

DATE: January 24, 1979

DESCRIPTION: Flood plain consists of hardwood trees, including many small-diameter trees, and very little ground cover. The surface is fairly smooth.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

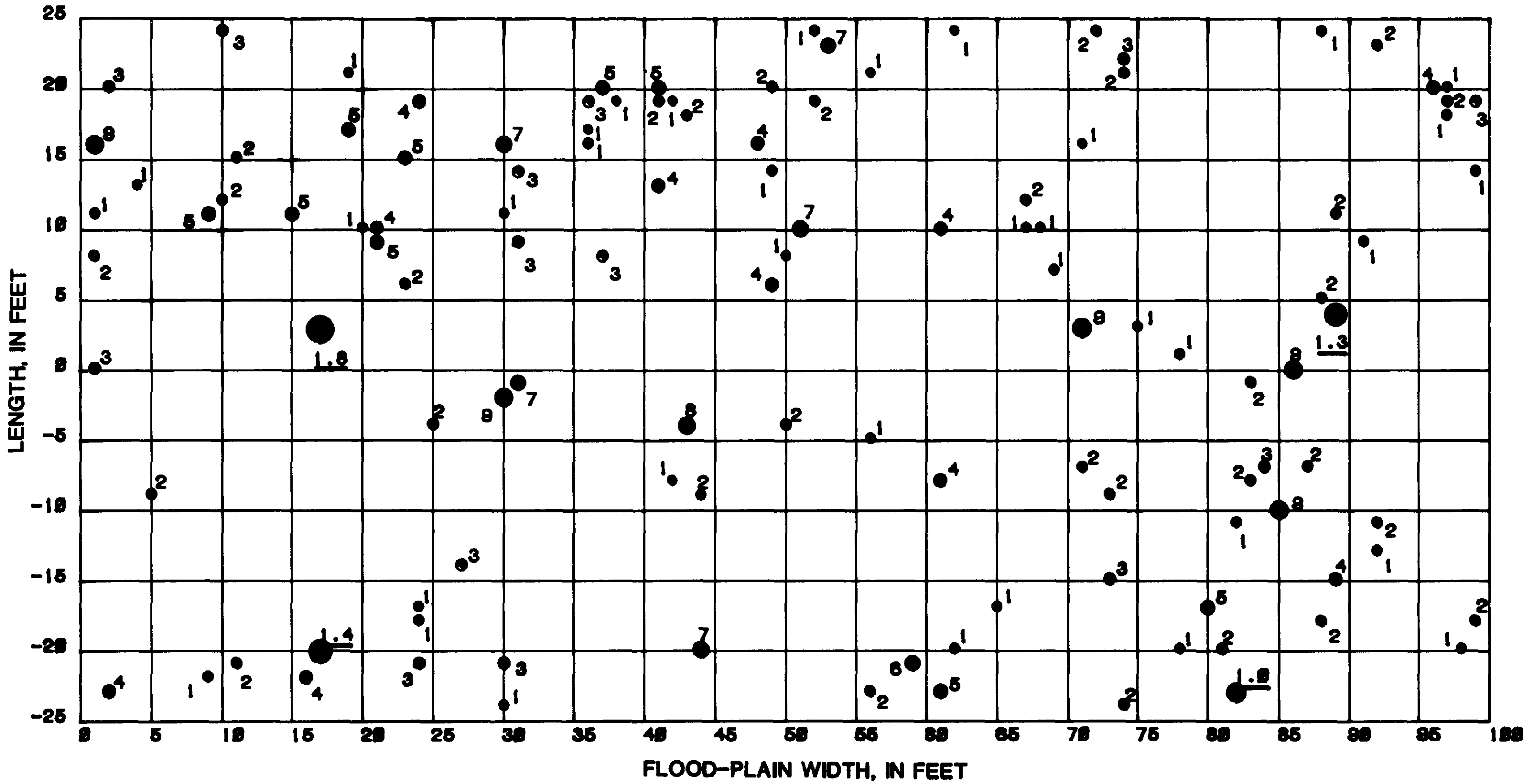
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 31.

SITE: Alexander Creek, cross section 600

DATE: January 24, 1979

DESCRIPTION: Flood plain consists of hardwood trees and some ground cover. The surface is fairly smooth.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

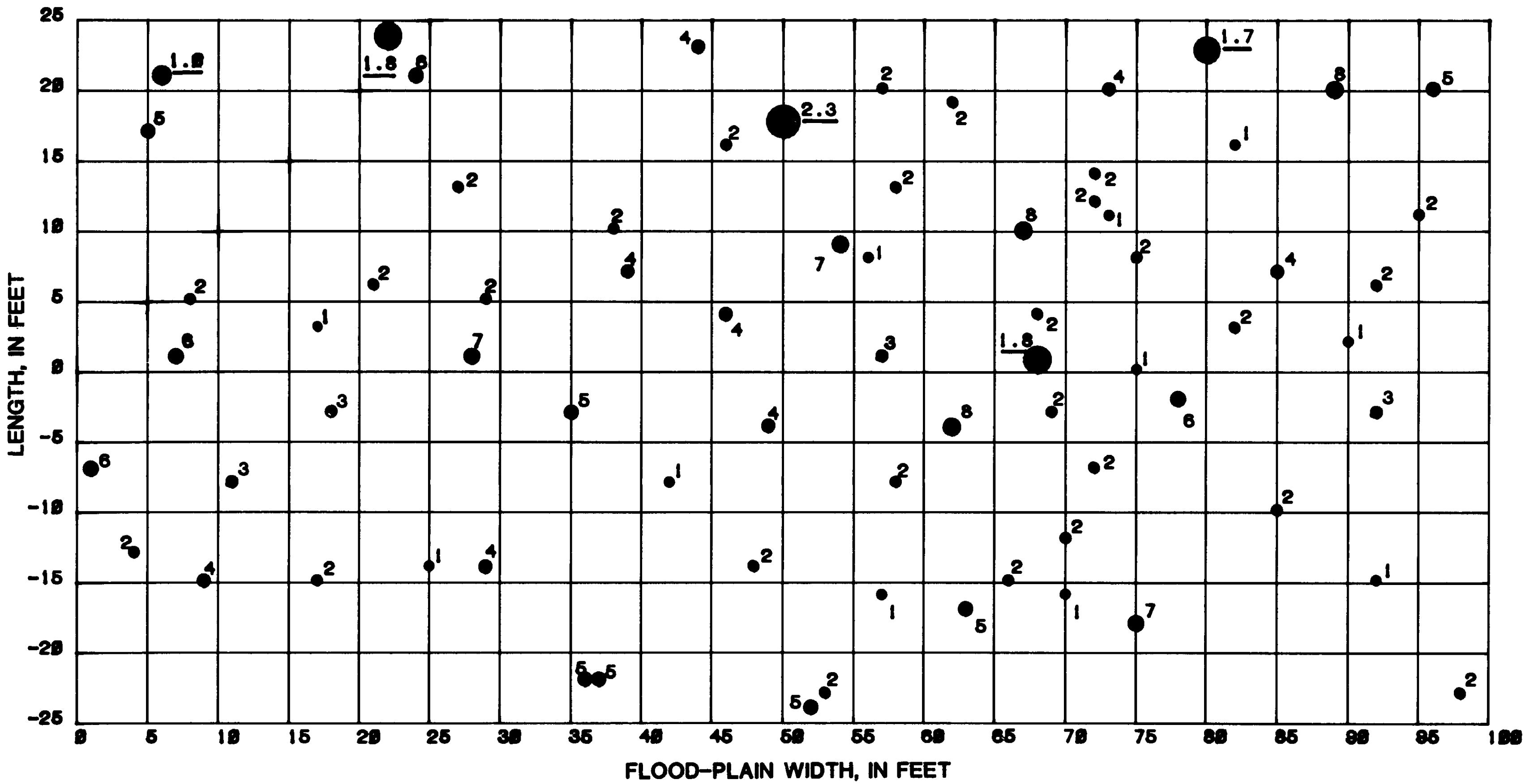
1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 32.

SITE: Comite River, cross section 300

DATE: January 17, 1979

DESCRIPTION: Flood plain consists of hardwood trees, including large-diameter trees, and very little ground cover. The surface is slightly irregular.



EXPLANATION

2 Location of tree; number indicates tree diameter in tenths of a foot

1.1 Location of tree; number underlined indicates tree diameter in feet

Figure 33.

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