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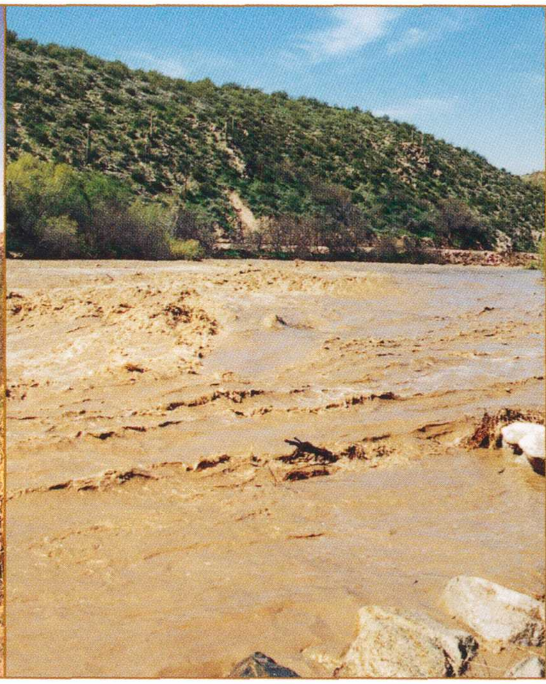
Method to Estimate Effects of Flow-Induced Vegetation Changes on Channel Conveyances of Streams in Central Arizona

Water-Resources Investigations Report 98–4040

Prepared in cooperation with the Flood Control District of Maricopa County



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Cover photographs: Three photographs of the same reach of the Hassayampa River near Wickenburg. Photographs were taken before, during, and after flow of February 15, 1995, and illustrate flow-induced changes to riparian vegetation conditions.

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By JEFF V. PHILLIPS, DAWN McDONIEL,
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Tucson, Arizona
1998

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
square foot (ft^2)	0.0929	square meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot-pound per second (ft-lb/s)	1.356	Newton-meter per second
pound per square foot (lb/ft^2)	47.88	Newton per square meter
pound per cubic foot (lb/ft^3)	157.1	Newton per cubic meter

VERTICAL DATUM

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Method to Estimate Effects of Flow-Induced Vegetation Changes on Channel Conveyances of Streams in Central Arizona

By Jeff V. Phillips, Dawn McDoniel, Joseph P. Capesius, *and* William H. Asquith

Abstract

Proper estimation of Manning's roughness coefficient, *n*, in open channels is necessary to reliably estimate channel conveyance—an important element of an open-channel hydraulic study. Proper estimation of *n* values, however, can be difficult in the arid to semiarid southwestern United States because floods may dramatically alter the roughness characteristics of the channel by (1) flattening or laying over vegetation, which acts to increase conveyance; and (2) removing vegetation in response to degradation of the substrate, which also acts to increase conveyance. Data collected during this investigation were used to develop a semiempirical relation to assist in *n*-value estimation for sites where flood induced changes in vegetation are considerable.

To investigate the potential for the flattening or laying over of vegetation in response to a flood, a site-specific vegetation-susceptibility index was developed. This index is a function of the type, density, and distribution of vegetation as well as the relation between depth of flow and vegetation height. In this study, it was determined that the flexural stiffness of vegetation is the primary control of the potential for the flattening or laying over of vegetation. The degree to which vegetation is affected by flow can be evaluated using the relation between stream power, which is a measure of energy transfer, and the vegetation-susceptibility index. To investigate the potential for vegetation removal, evaluation of substrate degradation and exposure and weakening of vegetation root systems is required. The potential for substrate degradation is related to boundary shear stress.

Channel-conveyance calculations made for preflow- and postflow-channel conditions indicate that incorrect assessment of vegetation conditions during the peak flow can result in water-surface elevation differences of as much as 2.63 feet when considerable changes in vegetation were observed. This scenario can lead to erroneous delineation of flood-prone areas and structure capacities. An example case is presented that illustrates the application of the relation that was developed in this study to assess the effects of flow-induced vegetation changes on computed channel conveyances and water-surface elevations of streams in central Arizona.

INTRODUCTION

In 1991, the U.S. Geological Survey (USGS), in cooperation with the Flood Control District of Maricopa County, began a 6-year study of flow-induced vegetation changes and the resultant effect on channel conveyances of streams in central Arizona. Because accurate calculation of channel conveyance is critical for open-channel hydraulic studies, a major objective of this study was to develop a relation to quantify the effects of flow-induced vegetation changes on channel conveyances and computed water-surface elevations. To accomplish this objective, considerable field work was performed at selected sites to collect the data that were needed to accurately characterize streamflow, vegetation, and channel conditions.

Computations of channel conveyance for open-channel flow require an evaluation of channel roughness. Channel roughness reflects the channel's resistance to flow and usually is expressed by a roughness coefficient. Manning's roughness coefficient, n, represents the composite effect of a variety of flow-resistance factors that include bed material, channel shape, and vegetation characteristics (Cowan, 1956). Cowan (1956) indicated that channel vegetation can have the greatest potential effect on the total roughness coefficient selected for a reach. Thomsen and Hjalmarson (1991) describe the major effect of vegetation on total roughness for streams in semiarid to arid climates typical of the southwestern United States. In these types of environments and in a period of only a few years, vegetation may grow to full maturity throughout the main channel of natural and manmade streams, which results in large increases in estimates of n (Aldridge and Garrett, 1973; Thomsen and Hjalmarson, 1991). Although the vegetation may appear substantial, peak flows that are powerful enough to lay over or remove vegetation often occur during moderate to large flooding in central Arizona (Burkham, 1976; Phillips and Hjalmarson, 1994). The flattened or removed vegetation markedly decreases preflow estimates of n. This decrease in n increases peak-flow channel conveyances and effectively lowers peak-flow water-surface elevation of the flow compared to preflow predictions.

Although past investigations have presented information useful for assessing the effects of peak flow on roughness characteristics of grasses in manmade channels (Ree and Palmer, 1949; Soil Conservation Service, 1954; Kouwen and Li, 1980; Temple, 1980; and Kouwen, 1992), almost no guidelines are available to evaluate the effects of flow on larger vegetation types such as brush and small trees that commonly grow throughout the main channel of streams in the southwestern United States (House and Pearthree, 1995, p. 3068). The ability of flows to substantially alter vegetation characteristics and the lack of adequate guidelines to assess these changes can result in uncertainties and erroneous channel-conveyance calculations. These uncertainties and errors could result in poor management of waterways, poor estimates of peak discharge, and improper design of bridges, culverts, road grades, and other water-related structures. The Flood Control District of Maricopa County funded this study in order to decrease the amount of uncertainty associated with estimating peak-flow vegetation conditions for channel-conveyance computations.

Purpose and Scope

The purpose of this report is to provide information and new methodologies to engineers, hydrologists, planners, and researchers so that better assessments can be made to determine variations of channel conveyance that result from changes in vegetation characteristics. Data collected for 26 peak flows at 19 sites in a 6-year period in central Arizona were used to assess flow-induced changes in vegetation conditions (fig. 1). A semiempirical relation that describes flow-induced changes in vegetation is presented as well as the subsequent effect of these changes on flow resistance. The changes in water-surface elevations for estimated preflow- and postflow-vegetation conditions were computed and presented for each of the study sites. The purpose of presenting this information is to illustrate potential errors that can accompany incorrect assessments of n values caused by flow-induced vegetation changes. An example case illustrates

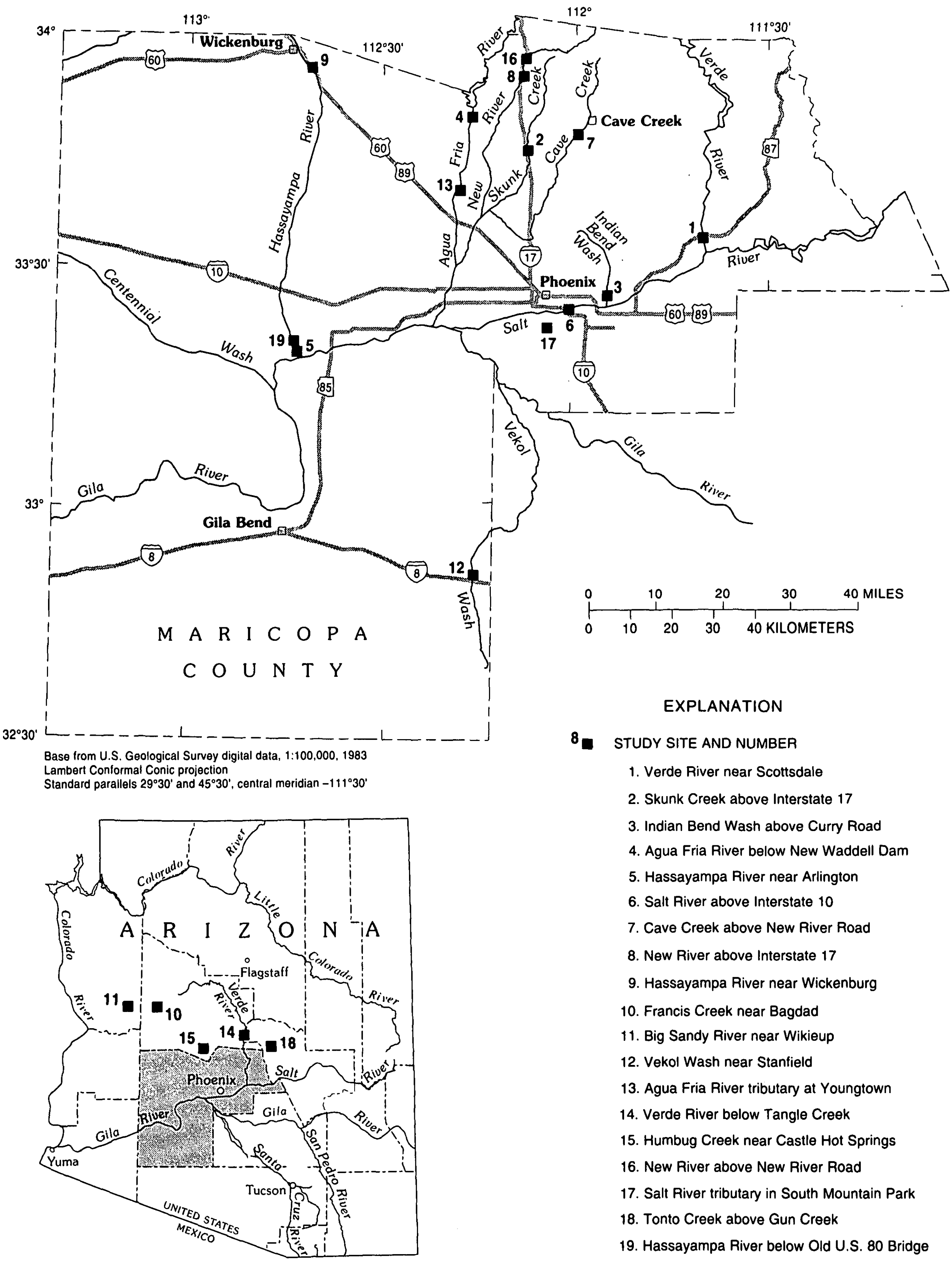

Figure 1. Study area and selected sites in central Arizona.

procedures for estimating *n* values for vegetated channels. In addition, many photographs are presented for visual representation of the substantial vegetation and channel changes that may occur during flows in semiarid to arid environments (See the section entitled "Basic Data" at the end of the report). The photographs also serve as a comparative aid for transferring the results of this study to sites with similar channel and vegetation characteristics.

This study was not an attempt to describe and quantify all the complex hydrodynamic processes that collectively affect vegetation and channel conditions during flows. Data, coefficients, and the semiempirical relation are presented in order to address the potential for erroneous open-channel conveyance calculations. Limerinos (1970) stated that it is unlikely that the determination of *n* values for natural channels will ever be an exact science, and the determination of channel conveyance when vegetation conditions are substantially altered by flow will always be difficult. The primary focus of this study was on vegetation growing in the main channel of streams; however, the effect of flow on overbank vegetation was evaluated at two of the study sites. The effect of flow on streambank vegetation was not assessed in this study.

Description of the Study Area

The basin and range topography of central Arizona generally is characterized by steep block-faulted mountains separated by gently sloping valleys composed of material eroded from the mountains. Elevation above sea level ranges from about 5,000 ft in the mountains to about 1,000 ft at the valley floors. The composition and stability of stream channels varies in the study area. Natural channels range from unstable predominantly sand channels to more stable gravel-bed channels composed of cobble- to boulder-sized bed material. Extremely stable bedrock channels also are found in the study area, but were not included in the investigation. Stream channels in or near urban areas generally are manmade and have soil cement, concrete, rip-rap, grouted and wire-enclosed rock, grass, or a combination of these materials (NBS Lowry Engineers and Planners and McLaughlin Water Engineers, 1992).

In the southern and western parts of central Arizona, stream channels typically are composed of sand-sized material, are ephemeral, and can undergo substantial change in geometry during flows. Vegetation often is found throughout the main channels of these streams. The unconsolidated and highly erodible nature of sand-dominated streams can result in root exposure and vegetation removal during flows. For the sand channels in this study, gradients range from 0.0036 to 0.0038 ft/ft and median diameter of the bed material ranges from about 0.6 to 1.0 mm. Gravel-bed streams are predominant in the northern and eastern parts of the study area and are characterized by larger substrate material (median diameter of bed material is greater than about 2 mm). Channel boundaries generally tend to be stable during low to moderate flows in gravel-bed channels; however, during large flows, large amounts of bed material may be displaced. Several of the gravel-bed channels used for this study are in river reaches where flow is regulated by reservoirs and diversions as well as in reaches that have been channelized.

Mean annual precipitation in the study area ranges from about 7 in. in the metropolitan area of Phoenix to more than 25 in. in the nearby mountains. Precipitation in central Arizona generally occurs in summer (June through October) and winter (December through March), and rainfall for both seasons is about equal (Sabol and others, 1990). In the summer, convective thunderstorms produce precipitation that is intense and short in duration and covers small areas. Summer storms frequently produce flash floods (Burkham, 1970). In the winter, regional-frontal systems produce precipitation that is relatively low in intensity, long in duration, and covers large areas. These storms can result in substantial runoff volumes and peak flows for large streams in the study area. Dissipating tropical cyclones—a third storm type—primarily occur in September and October (Hirschboeck, 1985; Webb and Betancourt, 1992). Although less frequent than the other types of storms, dissipating tropical cyclones have caused record floods that are regional in extent (Aldridge and Eychaner, 1984; Roeske and others, 1989).

The type, distribution, and density of vegetation in streams in the study area are highly variable. Vegetation types found in and along many streams in central Arizona include saltcedar, willow, cottonwood, mesquite, palo verde, and a variety of brush and grass species. The spatial distribution and density of vegetation near streams may depend on the availability, quality, and flow characteristics of the water. For example, in the few perennial streams, vegetation grows parallel to base-flow channels; whereas, in ephemeral channels, vegetation often grows randomly throughout the main channel.

Previous Investigations

Previous investigations have attempted to quantify the retarding effects of certain types of vegetation on flow. Most of these studies, however, were limited primarily to unchanging main-channel vegetation (Chow, 1959; Aldridge and Garrett, 1973; Thomsen and Hjalmarson, 1991), unchanging flood-plain vegetation (Petryk and Bosmajian, 1975; Arcement and Schneider, 1989; Fathi-Maghadam and Kouwen, 1997), and unchanging streambank vegetation (Jarrett, 1985; Masterman and Thorne, 1992; Coon, 1995). Some investigators have attempted to assess the effect of flow on grass growing in manmade channels and developed relations useful for estimation of the corresponding change in flow resistance associated with laid-over grasses (Ree and Palmer, 1949; Phelps, 1970; and Kouwen and Unny, 1973). Apart from a preliminary relation between flow and the flow-induced changes in vegetation conditions developed by Phillips and Hjalmarson (1994), and several other investigations that only marginally address this problem (Li and Shen, 1973; Burkham, 1976; and Ohlemutz, 1992), no comprehensive data set or methodologies exist for estimating the changes in channel conveyance that result from flow-induced changes in the condition of brush and small trees that commonly grow throughout the main channel of natural and man-made streams in semiarid to arid environments.

Phillips and Hjalmarson (1994) developed a simple empirical relation that describes the effects of flow on vegetation and is based on vegetation and flow data collected before, during, and after 13 flows at 11 sites in central Arizona. Average vegetation height was determined for preflow conditions, and the flow was described in terms of stream power. Stream power, which is a measure of energy transfer, was computed at cross sections on the basis of postflow-channel conditions. Phillips and Hjalmarson (1994, fig. 1) indicate that the effect of the flow (no effect, little effect, laid-over, or removed) on vegetation is related to stream power and vegetation height. Although the relation between stream power, vegetation height, and the effect of flow on the vegetation correlated well, there was a clear need for more detailed research and study of the physical characteristics of vegetation and the variable effects of flow on these conditions. The information and relation presented in this report are an extension of the work by Phillips and Hjalmarson (1994).

DATA COLLECTION AND ANALYSIS

Hydraulic data, vegetation data, and substrate data were collected for this investigation. Hydraulic data included measured or estimated discharge, water-surface profiles, and channel cross-section characteristics. Vegetation conditions, such as average height and density, were measured or estimated, described, and photographed before and after peak flows; thus, flow-induced changes to vegetation were documented shortly after flow subsided. Substrate data, which consist of the median diameter of bed material, were obtained either by visual examination or by measuring the intermediate axis of a representative population of particles.

Hydraulic Data

Although the determination of discharge is essential for many hydraulic studies, the actual power and force of the flow are better indicators of flow-induced changes in vegetation and substrate conditions. For example, Costa (1987) suggests that some floods in small basins with low unit discharges can produce values of shear stress and stream power per unit area of channel bed that are substantially greater than those for floods in large rivers. Additionally, Costa's (1987) findings indicate that the actual flow forces are more directly controlled by the magnitude of hydraulic conditions, such as channel slope and flow depth, and probably not the absolute discharge.

The absolute magnitude of peak discharge is not used directly in the derivation of the relation in this report; however, discharge data are presented for comparative purposes (table 1). Discharge data were obtained by direct current-meter measurement (Rantz and others, 1982), at a nearby USGS streamflow-gaging station that had a well defined stage-discharge relation, or by indirect peak-flow measurement (Dalrymple and Benson, 1967).

Stream Power and Shear Stress

A fundamental assumption of this investigation is that a critical stream power exists for specific vegetation conditions, and that vegetation will begin to bend when this critical stream power value is exceeded. Stream power is a measure of energy transfer in an open channel and, according to Simons and Richardson (1966), stream power is defined as:

$$SP = 62.4RS_wV, \tag{1}$$

where

SP = stream power, in foot-pounds per second per foot squared,
62.4 = specific weight of water, in pounds per cubic foot,
R = hydraulic radius, in feet,
S_w = slope of the water-surface profile, in feet per foot, and
V = average velocity, in feet per second.

Boundary shear stress (shear stress) is the force exerted on the bed by the moving water and is the hydraulic component most related to substrate or bedload movement (Vanoni, 1975; Carson and Griffiths, 1985). Shear stress is used instead of stream power to describe the potential for a flow to degrade the channel substrate. Consequently, shear stress is considered the predominant mechanism that potentially can expose and weaken root systems and remove vegetation. Shear stress, t_o, is the force per unit area exerted on the bed by the moving water and is defined (Davidian and Cahal, 1963) as:

$$t_o = 62.4RS_o, \tag{2}$$

where

62.4 = specific weight of water, in pounds per cubic foot;
R = hydraulic radius, in feet; and
S_o = bed slope, in feet per foot.

Vegetation Data

Adequately describing all the physical components that collectively characterize vegetation conditions in streams in Arizona is complex and difficult. In the study by Phillips and Hjalmarson (1994), the average height of vegetation measured before flow was the only component used to characterize vegetation conditions. Their simplified approach required various assumptions that ignored several important factors such as the variable flexural strength of different vegetation species.

In the course of this investigation, it was determined that additional physical components could more effectively model the effects of flow-induced changes to vegetation. The physical components include four vegetation attributes—(1) the flexural strength of specific types and sizes of vegetation, (2) the percent of flow blocked by vegetation, (3) the distribution of the vegetation, and (4) the depth of flow relative to the vegetation height (table 2).

Vegetation-Susceptibility Index

The vegetation attributes that were determined for each site (table 2) are incorporated into a single parameter called the vegetation-susceptibility index. The vegetation-susceptibility index is defined by

$$K_v = V_{flex}C_{blocking}C_{dist}C_{depth}, \tag{3}$$

Table 1. Hydraulic data collected for sites in central Arizona

[ft^3/s, cubic foot per second; ft/s, foot per second; ft, foot; ft/ft, foot per foot; $ft\text{-}lb/s/ft^2$, foot pound per second per foot squared; lb/ft^2, pound per foot squared]

Site number	Site name	Date of peak flow	Discharge (ft^3/s)	Average velocity (ft/s)	Hydraulic radius (ft)	Water-surface slope (ft/ft)	Stream power ($ft\text{-}lb/s/ft^2$)	Bed slope (ft/ft)	Boundary shear stress (lb/ft^2)
1a	Verde River near Scottsdale..	03–28–91	2,860	4.6	4.5	0.0013	1.7	0.0018	0.51
1b	Do.	08–24–92	16,000	7.0	9.5	.0012	5.0	.0018	1.07
1c	Do.	01–08–93	127,000	11.0	13.7	.0021	19.6	.0018	1.54
2a	Skunk Creek above Interstate 17........................	03–01–91	618	3.9	1.8	.0054	2.4	.0047	.53
2b	Do.	09–28–95	822	5.1	2.0	.0058	3.7	.0047	.59
3	Indian Bend Wash above Curry Road.........................	10–06–93	[1]6,480	6.6	5.5	.0015	3.4	.0013	.45
4	Agua Fria below New Waddell Dam......................	02–09–93	9,000	4.9	5.2	.0025	4.0	.0030	.97
5a	Hassayampa River near Arlington............................	01–08–93	11,400	9.0	6.0	.0040	13.5	.0034	1.27
5b	Do.	02–15–95	3,900	4.6	3.9	.0043	4.8	.0034	.83
6	Salt River above Interstate 10........................	01–08–93	129,000	11.1	13.2	.0018	16.5	.0021	1.73
7	Cave Creek above New River Road..........................	01–08–93	9,760	10.0	3.6	.0090	20.2	.0090	2.02
8	New River above Interstate 17........................	01–08–93	13,900	12.1	6.6	.0065	32.4	.0065	2.68
9a	Hassayampa River near Wickenburg........................	01–08–93	26,400	14.1	[1]7.2	.0049	31.0	.0036	1.62
9b	Do.	02–15–95	13,400	12.1	5.3	.0045	18.0	.0036	1.19
9c	Do.	08–14–95	5,540	8.0	3.9	.0040	7.8	.0036	.88
10	Francis Creek near Bagdad...	01–08–93	12,500	10.6	8.5	.0079	44.4	.0073	3.87
11	Big Sandy River near Wikieup..............................	02–09–93	68,700	17.1	11.6	.0036	44.6	.0035	2.53
	Do.[2]	Do.	Do.	3.2	3.9	.0034	2.6	.0019	.46
12	Vekol Wash near Stanfield....	09–10–94	6,590	9.2	4.5	.0050	12.9	.0054	1.52
13	Agua Fria River tributary at Youngtown.........................	12–10–91	18	.87	1.4	.0140	1.06	.0184	1.61
14	Verde River below Tangle Creek.................................	01–08–93	145,000	16.0	15.8	.0025	39.4	.0033	3.25
	Do.[2]	Do.	Do.	7.2	10.3	.0026	12.0	.0027	1.74
15	Humbug Creek near Castle Hot Springs........................	01–08–93	6,000	11.7	4.3	.0084	26.4	.0071	1.90
16	New River above New River Road.................	01–08–93	13,900	8.3	5.8	.0060	18.0	.0060	2.17
17	Salt River tributary in South Mountain Park....................	11–02–95	220	7.0	.9	.0270	10.6	.0270	1.52
18	Tonto Creek above Gun Creek..........................	01–08–93	72,500	15.2	15.9	.0063	95.0	.0030	2.98
19a	Hassayampa River below Old U.S. 80 Bridge............	01–08–93	11,400	10.2	4.6	.0038	11.1	.0038	1.09
19b	Do.	02–15–95	3,900	7.0	2.6	.0038	4.32	.0038	.62

[1]Revision of Phillips and Hjalmarson (1994).
[2]Overbank area.

Table 2. Vegetation data collected for sites in central Arizona

[ft, foot; %, percent; --, dimensionless; <, less than; >, greater than]

Site number	Vegetation type	Average vegetation height (ft)	Cross-section area of flow blocked by vegetation[1] (%)	Vegetation distribution	Ratio of hydraulic radius to height of vegetation (--)	Postflow-vegetation conditions
1a	Brush[2]	3	<30	Parallel	1.5	Erect
1b	Brush	3	<30	Parallel	3.2	Prone
1c	Saltcedar	13	30 to 70	Parallel	1.0	Prone
2a	Brush	3	30 to 70	Random	.6	Erect
2b	Brush	2	<30	Random	1.0	Prone
	Brush	5	<30	Random	.4	Erect
3	Brush	3	<30	Random	1.8	Erect
4	Saltcedar	8	30 to 70	Random	.6	Erect
5a	Brush	7	30 to 70	Parallel	.9	Prone
	Saltcedar	15	<30	Parallel	.4	Erect
5b	Saltcedar	12	<30	Parallel	.3	Erect
	Palo verde	10	<30	Random	.4	Erect
6	Brush	5	<30	Random	2.6	Prone
	Willow	18	<30	Parallel	.7	Erect
7	Brush	3	>70	Random	1.2	Removed
	Palo verde	16	<30	Random	.2	Erect
8	Brush	7	30 to 70	Random	.9	Removed
	Willow	13	<30	Random	.5	Prone
9a	Brush	5	30 to 70	Random	1.4	Removed
	Willow	18	30 to 70	Random	.4	Prone
9b	Willow	15	30 to 70	Random	.4	Removed
9c	Brush	6	<30	Random	.6	Prone
	Willow	15	<30	Random	.3	Erect
10	Willow	15	30 to 70	Parallel	.6	Prone
11	Brush	8	<30	Parallel	1.4	Prone
	Mesquite	16	>70	Random	.2	Erect
12	Willow	15	<30	Random	.3	Prone
13	Brush	12	>70	Random	.1	Erect
14	Brush	5	30 to 70	Random	3.2	Prone
	Willow	15	<30	Parallel	.7	Erect
15	Brush	4	<30	Random	1.1	Prone
	Willow	20	<30	Random	.2	Erect
16	Brush	4	30 to 70	Random	1.4	Removed
17	Brush	2	<30	Random	.4	Prone
	Palo verde	8	<30	Random	.1	Erect
18	Brush	6	<30	Parallel	2.6	Prone
19a	Willow	10	<30	Parallel	.5	Removed
19b	Saltcedar	7	<30	Parallel	.4	Removed

[1]Estimated on the basis of preflow-vegetation conditions.

[2]Brush is used as the generic term for sage brush, arrowweed, creosote, or burro bush. Physical attributes for these types of brush are assumed to be similar and are classified as one type.

where

K_v = vegetation-susceptibility index, in foot-pounds;

V_{flex} = vegetation-flexibility factor, in foot-pounds;

$C_{blocking}$ = vegetation-blocking coefficient;

C_{dist} = vegetation-distribution coefficient and

C_{depth} = flow-depth coefficient.

Information obtained from the sites was considered and utilized in the selection of values for $C_{blocking}$, C_{dist}, and C_{depth}. Values assigned to the three coefficients generally were determined for preflow conditions according to engineering experience gained during the course of this investigation.

Vegetation-Flexibility Factor

The vegetation-flexibility factor (V_{flex}; see equation 3) is the most significant factor in determining whether vegetation will bend or remain in a generally upright position when subjected to the power of flow. The unique physical properties of many types of vegetation enable them to bend to extreme angles when force is applied. The flexural strength or stiffness of different species of vegetation is not constant, and the degree of bending varies for a given applied force. The force required to bend or lay over vegetation, therefore, was quantified to obtain the flexural strength of different vegetation types. For the purposes of this report, laid over is defined as a condition in which vegetation is bent more than 45° from vertical.

Dynamometers, which are mechanical devices that measure magnitude of tension in cables, were used to determine the force required to lay over four types of vegetation. The vegetation included saltcedar, willow, mesquite, and palo verde, and ranged in height from 3 to 18 ft. Bending moments were determined by computing the product of the moment arm (distance from the base or pivot point to the location where force was applied) and the force required to bend the vegetation to 45° from the vertical (fig. 2; table 13, see the section entitled "Basic Data" at the end of the report).

Attempts were made to place the dynamometer at a vertical distance from the base of the vegetation of about 0.4 times the height of the vegetation (table 13, see the section entitled "Basic Data" at

Figure 2. Dynamometers used to determine vegetation bending-moment values.

the end of the report). Because of logistical constraints, such as protruding branches, however, the dynamometer was not always placed at this position on the vegetation. The relation of bending moment to height of vegetation was determined for each vegetation type (fig. 3). Additionally, equations were developed by regression techniques of the bending moment with height for each of the four vegetation types (table 3).

Table 3. Regression equations relating bending moment to vegetation height for saltcedar, willow, mesquite, and palo verde

[BM, bending moment in foot pounds; H, height of vegetation in feet]

Vegetation type	Equation	Coefficient of determination (r^2)
Saltcedar...............	$BM = 10^{0.102H + 0.880}$	0.87
Willow..................	$BM = 10^{0.122H + 0.581}$	.98
Mesquite...............	$BM = 10^{0.124H + 0.935}$	.88
Palo verde............	$BM = 10^{0.171H + 0.848}$	.86

The bending moment (also referred to as flexural strength or stiffness) of the vegetation at varying heights can be estimated from the equations in table 3. For example, a flexural strength of 63.2 ft-lb is estimated for a 10-foot-tall willow; whereas, a flexural strength of 361 ft-lb is estimated for a 10-foot-tall palo verde. The assumption, therefore, is that a lone palo verde in midchannel, is thought to be substantially more likely to resist bending when it is subjected to a similar magnitude of stream power and similar degree of submergence as a lone willow tree in midchannel.

Although uncertainties are associated with this simplified approach, data collected during this investigation seem to support these assumptions. For example, figure 4 shows a lone willow about 15 ft tall that was laid over during a flow of 6,590 ft^3/s; whereas, figure 5 shows a lone 16-foot-tall palo verde that remained erect throughout a flow of 9,760 ft^3/s. Duration of flow for the events was about equal. The magnitude of stream power that affected the palo verde was 20.2 $ft\text{-}lb/s/ft^2$; whereas, the magnitude of stream power to which the willow was subjected is equal to 12.9 $ft\text{-}lb/s/ft^2$ (table 1). These data indicate that the large flexural strength of the palo verde enabled it to resist the stream power that was substantially larger than the computed stream power that altered or laid over a willow with similar dimensions. The

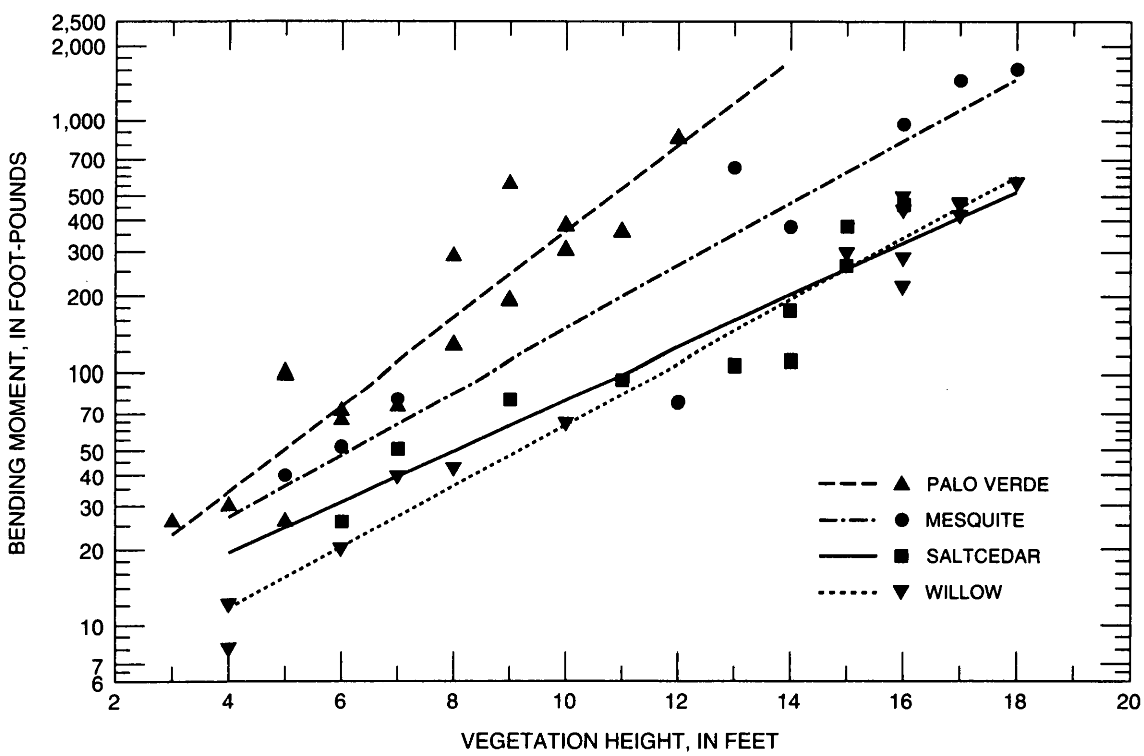

Figure 3. Bending-moment values for four types of vegetation in central Arizona.

Figure 4. A lone willow approximately 15 feet tall in a prone position after the flow of September 10, 1994, Vekol Wash near Stanfield (ratio of hydraulic radius to height of vegetation was 0.3 and average velocity was 9.2 feet per second).

Figure 5. An erect 16-foot-tall palo verde after the flow of January 8, 1993, Cave Creek above New River Road (ratio of hydraulic radius to height of vegetation was 0.2 and average velocity was 10.0 feet per second).

average height of vegetation was determined for conditions at each site, and a corresponding flexural-strength value was computed using the equations in table 3.

In determining flexural strength, it was assumed that different types of vegetation behave in a similar manner when subjected to force. The vegetation types that were studied, however, differ somewhat in appearance and physical characteristics. For example, mesquite and palo verde are characterized by many major branches radiating out from the base; whereas, willow, commonly referred to as a pole tree (Stromberg and others, 1993), is characterized by a main trunk with minor branches from top to bottom. Differences in response to forces from streamflow might not be sufficiently accounted for by bending-moment values alone and thus form an inherent uncertainty associated with this study.

Trunk diameter could be a more applicable and physically correct component than vegetation height in determining flexural strength. Vegetation height, however, is a much more practical component to obtain in the field. In addition, determining a representative diameter for certain types of vegetation is difficult. The strong dependence of vegetation stiffness to vegetation height allows for a straightforward approach to estimating vegetation components in the field.

A separate analysis of the flexural strength of arrowweed and other types of brush was not made. Flexural strength of brush studied during this investigation is assumed to be similar to that of willow and was determined from bending-moment values obtained for willow (table 3).

Vegetation-Blocking Coefficient

The flexural strength of vegetation was obtained by only considering the force required to lay over the main stem of the vegetation. Consequently, the actual percentage of the flow area that is blocked by vegetation was measured to account for the combined resistant force associated with the vegetation. The $C_{blocking}$ value was determined for each site by assigning a weighted value to the estimated percentage of the cross-sectional area of flow that was blocked by vegetation for preflow conditions (table 4).

Table 4. Vegetation-blocking coefficients for selected categories

[<, less than; >, greater than]

Amount of flow blocked by vegetation, in percent	Vegetation-density coefficient, dimensionless
<30	1.0
30 to 70	4.0
>70	9.0

Vegetation-Distribution Coefficient

Collected data for this report suggest that the spatial distribution of riparian vegetation in natural and constructed channels could substantially influence the effects of flow on the vegetation. Vegetation aligned parallel to the direction of flow that generally is the result of consistent base flow (fig. 6*A*) can result in the redistribution of velocities across the channel section because of the combined resistant effect of the vegetation. The combined resistance causes a decrease in the velocities at the immediate location of the vegetation and mitigates the effects of flow on vegetation conditions. Past experiments in controlled laboratory environments resulted in similar conclusions (Li and Shen, 1973). For vegetation conditions categorized as randomly distributed (fig. 6*B*), velocity profiles are assumed to remain fairly constant across the channel. Dimensionless vegetation-distribution coefficients (C_{dist}; see equation 3), therefore, were determined for two categories—vegetation aligned parallel to the flow and vegetation distributed randomly throughout the main channel (table 5). Determination of the C_{dist} value (parallel or random) is subjective and requires a certain amount of experience and engineering judgment.

Table 5. Vegetation-distribution coefficients for vegetation orientation

Orientation to flow	Vegetation-distribution coefficient, dimensionless
Parallel	3.0
Random	1.0

A.

B.

Figure 6. Spatial distribution of vegetation in stream channels. *A*, Vegetation aligned parallel to flow. *B*, Randomly distributed vegetation.

Flow-Depth Coefficient

Flows in vegetated channels do not always result in total submergence of the vegetation. The effect of flow on vegetation depends on the depth of flow in relation to vegetation height (fig. 7).

The force required to lay over vegetation is inversely related to the length of the moment arm, or, in the case of flow effects on the vegetation, the depth of flow (fig. 8). This relation reinforces the assumption that as flow depth increases, the ability of vegetation to resist the effects of flow will decrease (figs. 7–8). Dimensionless flow-depth coefficients (C_{depth}; see equation 3) were determined for five different categories that are defined by the ratio of hydraulic radius to vegetation height (table 6). The hydraulic radius is assumed to approximate mean-flow depth as well as the approximate depth of flow at the immediate location of the vegetation.

Table 6. Flow-depth coefficients

[<, less than; >, greater than]

Ratio of hydraulic radius to average vegetation height	Flow-depth coefficient, dimensionless
<0.4	60
0.4 to 0.6	20
0.7 to 0.9	5
1.0 to 1.5	3
>1.5	1

Relation Between Stream Power and Vegetation-Susceptibility Index

The vegetation-susceptibility indices (eq. 3) were calculated, and the vegetation-susceptibility index was plotted with the stream power for each studied flow (table 7; fig. 9). If the vegetation-susceptibility index is high and computed stream power is low, the vegetation is not substantially affected (fig. 9). As stream power increases, however, the ability of the flow to lay over vegetation increases. A vegetation-susceptibility threshold is represented by the line shown on figure 9. The line is defined by the equation

$$SP = 2.054K_v^{0.231} \qquad (4)$$

In general, for flows that plot above this line, the vegetation can be expected to lay over assuming the characteristics of the vegetation and stream power of the flow in question are within values studied for this report.

Vegetation removal does not necessarily depend on initial proneness of the vegetation. Although the power of flow may not be of sufficient magnitude to substantially lay over the vegetation, the flow may still be large enough to degrade the channel substrate to the point that the vegetation's root system is exposed and may result in total removal of the vegetation. Data from flows that removed the majority of the channel vegetation, therefore, were not used for the relation in figure 9.

Vegetation Removal

Vegetation removal or its complete destruction primarily is dictated by the degree of channel-bed and boundary degradation, which in turn is influenced by the magnitude of the shearing forces of flow. Depending on the size of bed material and the size and type of vegetation, two distinct mechanisms for vegetation removal were observed in this investigation. The first mechanism (vegetation scour) is the exposure of root systems and removal of vegetation from transport of sand- and gravel-sized bed material. The second mechanism (vegetation obliteration) is the movement of cobble- and boulder-sized material onto the vegetation that results in the destruction of brush and small trees (fig. 10). Although obliteration occurred at several sites, degradation of channel boundaries and actual scour of root systems is considered the primary mechanism that causes vegetation removal.

The primary components that require quantification to evaluate the degree of vegetation removal include (1) the mean size of the substrate material, (2) the flow duration, and (3) the estimated size and density of the vegetation-root system. Mean size of the substrate material for alluvial channels studied generally was determined by sieve analysis. For substrate material that was too large to sieve, mean diameter was determined by measuring the intermediate axis of a representative number of particles or estimated on

Figure 7. Saltcedar that was little affected by flow primarily because of the relatively low ratio of flow depth to vegetation height.

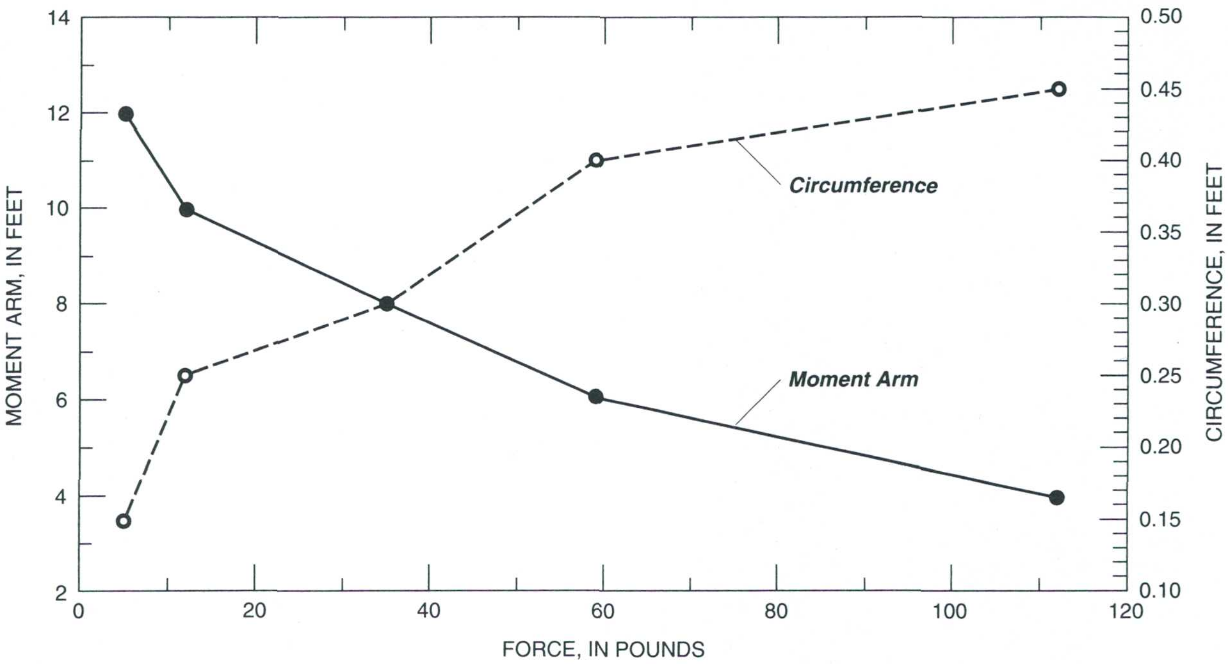

Figure 8. Relation between moment arm and the force required to bend vegetation to 45° past vertical. Circumference was measured at the immediate location in which the dynamometer was placed. A 15-foot-tall saltcedar was used for this example.

Table 7. Vegetation and channel characteristics and coefficients determined for sites in central Arizona

[ft-lb, foot-pound; --, dimensionless]

Site number	Vegetation-flexibility factor V_{flex} (ft-lb)	Vegetation-blocking coefficient $C_{blocking}$ (--)	Vegetation-distribution coefficient C_{dist} (--)	Flow-depth coefficient C_{depth} (--)	Vegetation-susceptibility index K_v (ft-lb)
1a	8.85	1.0	3.0	3.0	79.7
1b	8.85	1.0	3.0	1.0	26.6
1c	161	4.0	3.0	3.0	5,800
2a	8.85	4.0	1.0	20	708
2b	6.68	1.0	1.0	3.0	20.0
	15.5	1.0	1.0	20	310
3	8.85	1.0	1.0	1.0	8.85
4	49.7	4.0	1.0	20	3,980
5a	27.2	4.0	3.0	5.0	1,630
	257	1.0	3.0	20	15,400
5b	127	1.0	3.0	60	22,900
	361	1.0	1.0	20	7,220
6	15.5	1.0	1.0	1.0	15.5
	598	1.0	3.0	5.0	8,970
7	8.85	9.0	1.0	3.0	239
	3,840	1.0	1.0	60	230,000
8	27.2	4.0	1.0	5.0	544
	147	1.0	1.0	20	29,400
9a	15.5	4.0	1.0	3.0	186
	598	4.0	1.0	20	47,800
9b	258	4.0	1.0	20	20,600
9c	20.6	1.0	1.0	20	412
	258	1.0	1.0	60	15,500
10	258	4.0	3.0	20	61,900
11	36.1	1.0	3.0	3.0	325
	830	9.0	1.0	60	448,000
12	258	1.0	1.0	60	15,500
13	111	9.0	1.0	60	59,900
14	15.5	4.0	1.0	1.0	62.0
	258	1.0	3.0	5	3,870
15	11.7	1.0	1.0	3.0	35.1
	1,050	1.0	1.0	60	63,000
16	11.7	4.0	1.0	3.0	140
17	6.68	1.0	1.0	20	134
	164	1.0	1.0	60	9,840
18	20.6	1.0	3.0	1.0	61.8
19a	63.2	1.0	3.0	20	3,790
19b	39.3	1.0	3.0	20	2,360

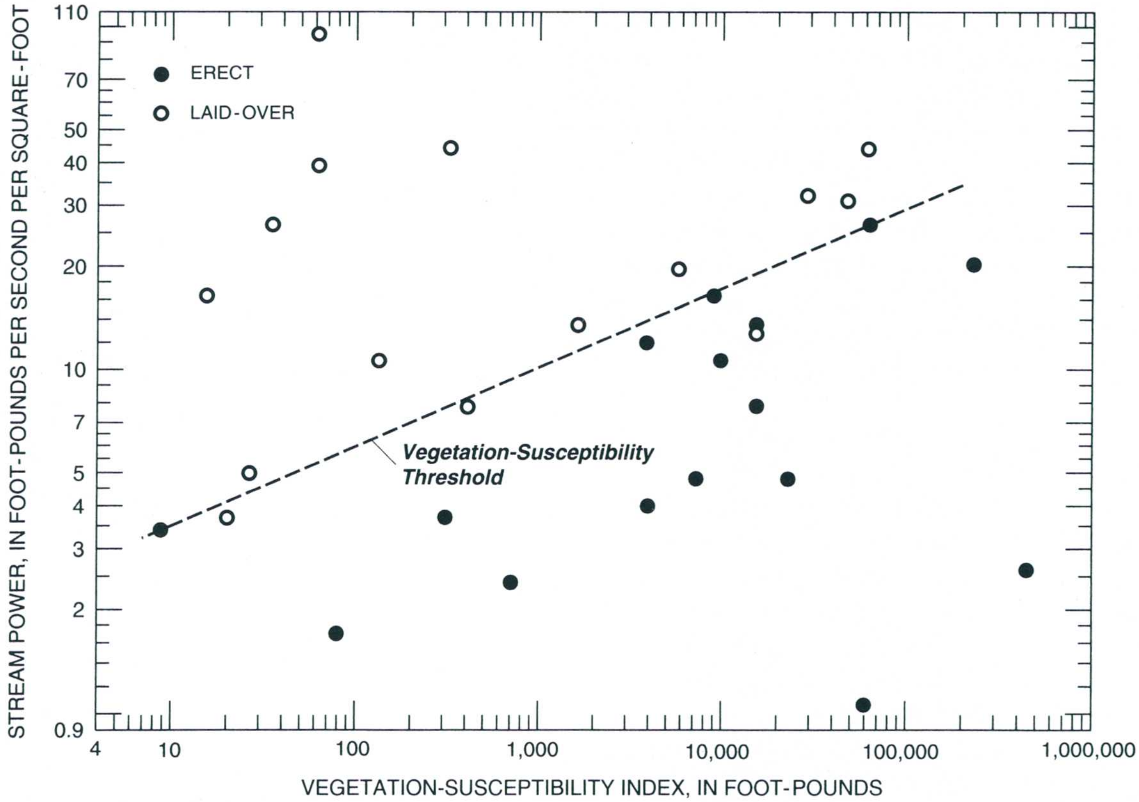

Figure 9. Vegetation conditions resulting from 22 flows at 17 sites, as a function of stream power and the vegetation-susceptibility index. The equation for the line in the figure is, $SP = 2.054\ K_v^{0.231}$.

Figure 10. Effect of transported cobbles and boulders on riparian vegetation.

the basis of collected field data and descriptions of the bed material. The flow duration is important because long-duration flows have a greater potential for significant movement of substrate material (table 8). Finally, estimating the size and density of vegetation-root systems (thus its strength) proved to be unattainable for this study. The complex nature of vegetation-root systems and the difficulty in determining their strength and size made developing a relation for vegetation removal impractical until more data become available.

Critical Shear Stress

Sediment size is an important factor in determining the ability of shear stresses to degrade substrate material and subsequently remove vegetation. In general, as particle size increases, the amount of shear stress required to initiate movement also increases (Shields, 1936). The magnitude of shearing forces required to initiate movement of bed material is called the tractive or critical shear stress (Vanoni, 1977). Several investigators have presented empirical relations used to determine the critical shear stress for specific sizes of bed material (Vanoni, 1975). For stream channels presented in this report that contain substrate material with a median diameter (d_{50}) less than 10 mm, an equation presented by Vanoni (1977) is used to determine critical shear stress. This equation is

$$t_c = 0.016\exp\left[0.1269\left(\ln d_{50}/0.1\right)^2\right], \quad (5)$$

where

t_c = critical shear stress, in pounds per square foot, and

ln = logarithm to the base e.

For channels containing substrate material with a d_{50} larger than 10 mm, an equation presented by Carson and Griffiths (1985) is used to determine critical shear stress. This is equation is

$$t_c = 0.0127 d_{50}\,. \quad (6)$$

The values of shear stress were divided by the critical shear stress (table 1 and table 8). For sites where the shear stress (eq. 2) during peak flow is less than the critical shear stress, channel boundaries are considered stable and vegetation removal is unlikely.

Flow Duration

One important factor in sediment transport not considered by the critical shear-stress equations is the duration that the bed material is subjected to shear stresses greater than the critical shear stress ($t_o/t_c > 1.0$). Peak flows in Arizona can be either short-duration flows that are characterized by sharp rises and falls in stage or long-duration flows that are characterized by gradual changes in stage. Short-duration peak flows typically occur in small basins (<50 mi^2) as a result of intense and short-duration thunderstorms. Long-duration peak flows generally result from winter storms generated by frontal systems and generally cover large areas (>50 mi^2). The long-duration flows also occur as a result of reservoir operations. Reservoir releases can last for many hours, days, or even weeks. For each flow, the approximate duration (in seconds) that the substrate material was subjected to shear forces greater than the critical shear stress was estimated on the basis of stage or hydrograph data where available (table 8).

A predictive method for vegetation removal or obliteration is not presented; however, it is hoped that the information and photographs presented in this section and the section entitled "Basic Data" at the end of the report will aid in the evaluation of substantial changes in roughness characteristics that occur when vegetation is removed from channel boundaries. At the three sites where vegetation removal occurred, the channel substrate generally was composed of sand-sized material (table 8). For the three sites where the vegetation was obliterated, the channel substrate was composed of cobbles (table 8).

When vegetation is completely removed by flow, a dramatic decrease in flow resistance can result, which increases channel conveyance and subsequently lowers water-surface elevations. As the uprooted vegetation is transported downstream, however, it may accumulate on more resistant vegetation (figs. 5 and 7) and manmade structures, such as bridge piers and culverts, which can dramatically decrease channel conveyance and

Table 8. Bed-material, shear-stress, and flow-duration components determined for sites in central Arizona

[lb/ft^2, pound per foot squared; s, seconds; N/A, not available; ---, no data]

Site number	Vegetation type	Median diameter (d_{50}) Millimeters	Median diameter (d_{50}) Feet	Shear stress t_o (lb/ft^2)	Critical shear stress t_c (lb/ft^2)	Ratio of shear stress to critical shear stress t_o/t_c (dimensionless)	Estimated flow duration (s)	Vegetation removed
1a	Brush	110	0.36	0.51	1.40	0.36	([1])	No
1b	Brush	110	.36	1.07	1.40	.76	---	No
1c	Saltcedar	110	.36	1.54	1.40	1.10	14,400	No
2a	Brush	88	.29	.53	1.12	.47	---	No
2b	Brush	88	.29	.59	1.12	.53	---	No
	Do.	88	.29	.59	1.12	.53	---	No
3	Brush	[2]N/A	[2]N/A	.45	---	---	---	No
4	Saltcedar	85	.28	.97	1.08	.90	---	No
5a	Brush	88	.29	1.27	1.12	1.13	3,600	No
	Saltcedar	88	.29	1.27	1.12	1.13	3,600	No
5b	Saltcedar	88	.29	.83	1.12	.74	---	No
	Palo verde	88	.29	.83	1.12	.74	---	No
6	Brush	94	.31	1.73	1.19	1.45	14,400	No
	Willow	94	.31	1.73	1.19	1.45	14,400	No
7	Brush	100	.33	2.02	1.27	1.59	3,600	Yes[3]
	Palo verde	100	.33	2.02	1.27	1.59	3,600	No
8	Brush	150	.49	2.68	1.90	1.41	5,400	Yes[3]
	Willow	150	.49	2.68	1.90	1.41	5,400	No
9a	Brush	1.0	.003	1.62	.03	54	3,600	Yes[4]
	Willow	1.0	.003	1.62	.03	54	3,600	No
9b	Willow	1.0	.003	1.19	.03	40	3,600	Yes[4]
9c	Brush	1.0	.003	.88	.03	29	3,600	No
	Willow	1.0	.003	.88	.03	29	3,600	No
10	Willow	400	1.3	3.87	5.08	.76	---	No
11	Brush	21	.07	2.53	.27	9.4	7,200	No
	Mesquite	21	.07	.46	.27	1.7	7,200	No
12	Willow	30	.10	1.52	.38	4.0	3,600	No
13	Brush	[2]N/A	[2]N/A	1.61	---	---	---	No
14	Brush	120	.39	3.25	1.52	2.14	7,200	No
	Willow	120	.39	1.74	1.52	.80	---	No
15	Brush	100	.33	1.90	1.27	1.50	1,800	No
	Willow	100	.33	1.90	1.27	1.50	1,800	No
16	Brush	150	.49	2.17	1.90	1.14	5,400	Yes[3]
17	Brush	49	.16	1.52	.62	2.45	900	No
	Palo verde	49	.16	1.52	.62	2.45	900	No
18	Brush	130	.43	2.98	1.65	1.81	5,400	No
19a	Willow	.6	.002	1.09	.02	54	3,600	Yes[4]
19b	Saltcedar	.6	.002	.62	.02	31	3,600	Yes[4]

[1]Removal is not considered possible, and flow duration not estimated if ratio of shear stress to critical shear stress is less than 1.
[2]Channel boundaries are partially composed of soil cement or firm earth and are considered stable.
[3]Obliterated.
[4]Scoured.

subsequently raise water-surface elevations in that local area.

EFFECTS OF FLOW-INDUCED VEGETATION CHANGES ON CHANNEL CONVEYANCES

To determine the effect of flow-induced vegetation changes on channel conveyance, the overall effect of vegetation changes on Manning's roughness coefficient (n) must be quantified. Knowledge of the factors that exert the greatest influence on n in natural and manmade channels is needed to adequately describe and quantify total energy losses.

Components of Manning's *n*

The general approach for estimating flow resistance in stream channels is to first select a base value of Manning's n for the bed material (n_b; Thomsen and Hjalmarson, 1991). The base n value represents the size and shape of the grains of the material along the wetted perimeter (Chow, 1959). Cross-section irregularities, channel alignment, vegetation, obstructions, and other factors that increase roughness then are added to n_b. The following equation, first introduced by Cowan (1956), is used to calculate the total composite n for a channel

$$n = (n_b + n_1 + n_2 + n_3 + n_4)\, m \qquad (7)$$

where

- n_b = base n value for a straight uniform channel;
- n_1 = surface irregularities;
- n_2 = variations in shape and size of the channel;
- n_3 = obstructions;
- n_4 = vegetation; and
- m = correction factor for meandering or sinuosity of the channel.

Detailed explanations for each adjustment factor can be found in Cowan (1956), Chow (1959), Aldridge and Garrett (1973), Jarrett (1985), Thomsen and Hjalmarson (1991), and Coon (1995).

Base Value of Manning's *n*

Most sites in this study were selected for reach and cross-sectional uniformity. Thus, the composite n value is considered a function of only n_b and an adjustment for the vegetation component, n_4. The other components at most of the sites were considered to have a negligible effect on total roughness.

Although the composite n value was considered verified at several sites (Phillips and Ingersoll, 1998), most sites required n-value estimation. A variety of techniques have been presented in literature that aid in estimating n values. Reference to published tables and photographs of verified n values is one method; another is the use of equations that relate n values to measurable channel and hydraulic components.

For sites having gravel-bed channels where the n value was not verified, n_b was primarily estimated on the basis of a recently developed equation for gravel-bed streams in central Arizona (Phillips and Ingersoll, 1998). The equation relates n_b to flow depth (represented as hydraulic radius, R) and the median size of the bed material and is defined as

$$n_b = 0.0926R^{1/6} / 1.46 + 2.23\log(R/d_{50}). \qquad (8)$$

The verified n value and not equation 8 was used at sites where a roughness coefficient could be back calculated from direct-current measurement and Manning's equation. Verified n values were not available for flows at the sand-dominated sites. The base n value at these sites was estimated on the basis of reference tables in Aldridge and Garrett (1973), Thomsen and Hjalmarson (1991), and Phillips and Ingersoll (1998).

Adjustment for Vegetation Component

If the flow forces are large enough to degrade the channel substrate to the degree that vegetation is removed before peak flow, the value of the adjustment for vegetation (n_4) approaches zero; and therefore, the vegetation would not significantly affect peak-flow conveyance computations. Vegetation such as grass flattened over the bed material in a gravel-bed channel may actually result in less resistance to flow than if the vegetation was not present. For most conditions, however, if the vegetation is not removed but is laid over, the degree to which flow resistance is affected is a factor that must be considered and evaluated. Under these conditions, a value for n_4 must be assigned. For example, figure 9 is used to roughly estimate whether or not the forces of flow will lay over (angle exceeding 45° from the vertical) vegetation. The resistance to flow attributed to vegetation at 45° from vertical can still be substantial under certain conditions such as low-flow depths. The streamlining of vegetation when it is laid over also may require consideration and would make the assessment of n_4 under these conditions very difficult.

Unfortunately, very few studies have actually isolated and verified n_4 under controlled conditions. Phillips and Ingersoll (1998) developed an equation that relates percentage of flow blocked by vegetation to the corresponding magnitude of n_4. This equation is as follows:

$$n_4 = 0.0008B - 0.0007, \qquad (9)$$

where

B = percentage of flow blocked by vegetation.

Values of B used in the derivation of equation 9 ranged from 3 to 25 percent. Results from the equation are questionable if the equation is used for sites where vegetation conditions are substantially beyond the range of data used in its derivation (Phillips and Ingersoll, 1998).

Values of n_4 were determined for each site for preflow- and postflow-vegetation conditions using available guidelines and equation 9. These values were added to the estimates of n_b to obtain the total roughness coefficient. The complex dynamics and highly variable nature of flow-induced changes in vegetation conditions, however, serve to maintain a certain degree of uncertainty and subjectivity in selections of n_4 and subsequent conveyance computations.

Channel-Conveyance Computations

Channel conveyance was calculated for preflow- and postflow-channel conditions at each of the sites to illustrate the potential differences in conveyance values attributed to inaccurate assessment of vegetation conditions for peak-flow computations. Channel conveyance was calculated using standard procedures (Dalrymple and Benson, 1967). Channel conveyance, K, is defined as

$$K = (1.486/n)AR^{2/3}, \qquad (10)$$

where

A = cross-section area, in square feet.

The changes in water-surface elevations for preflow and postflow conditions also were computed (table 9). Discharges were held constant for these computations, and water-surface elevations were determined by an iterative procedure. Potential errors in n-value estimates can result in substantial differences in calculated water-surface elevations (table 9). Recurrence intervals for most of the flows in this study ranged from 1 to 20 years. The difference in water-surface elevations when n_4 is incorrectly assessed, however, can be much greater for larger discharges such as those with recurrence intervals of 50 and 100 years.

Discussion and Example Case

Preflow assessment of roughness coefficients must be made for a variety of hydraulic studies that include delineation of floodways and design of hydraulic structures. Inaccurate assessment of peak-flow roughness conditions made before flow in densely vegetated channels can result in substantial errors. For example, the Hassayampa River below Old U.S. 80 Bridge site has dense growths of saltcedar and willow from time to time. The almost continuous irrigation return flow at this site contributes to accelerated vegetation growth, and subsequent to either artificial or natural removal, the vegetation is often near maturity after several growing seasons. Estimates of n_4 can be quite substantial and can even exceed the estimated value of n_b. Main-channel vegetation for this site, however, can be removed by flow magnitudes slightly larger than the 2-year flow (Garrett and Gellenbeck, 1991, p. 578, and table 1), which makes the selection of n_4 for this site difficult. Use of the relation presented in this report, however, can dramatically decrease the uncertainty associated with the selection of n_4 for sites where vegetation conditions may be altered by flow.

Table 9. Estimated preflow and postflow roughness coefficients and computed changes in water-surface elevations

Site number	Estimated preflow roughness coefficient	Estimated postflow roughness coefficient	Change in water-surface elevation, in feet
1a	0.030	[1]0.030	0.00
1b	.035	.032	.34
1c	.045	.037	2.17
2a	.048	[1].048	0
2b	.038	[1].035	.12
3	.030	[1].026	.55
4	.041	[1].041	0
5a	.041	.026	1.71
5b	.038	.026	.20
6	.034	.029	1.32
7	.040	.033	.45
8	.050	.035	1.00
9a	.040	.025	2.51
9b	.050	.025	2.60
9c	.035	.032	.22
10	.075	.060	1.73
11	.034	.029	1.22
	.080	.080	0
12	.040	.035	.43
13	.200	.200	0
14	.040	.030	2.63
	.050	.050	0
15	.046	.041	.36
16	.045	.040	.43
17	.035	.033	.04
18	.048	.043	1.23
19a	.035	.025	1.13
19b	.045	.025	1.18

[1]Verified *n* values (Phillips and Ingersoll, 1998).

Example case.—Consider a rectangular channel where computation of the flood elevation of the 100-year flow is needed. The channel reach is uniform in shape and bed-material composition. The bed material is dominated by cobbles with a d_{50} of 0.30 ft. Brush and willow are present throughout the study reach and distributed randomly in the channel. The average height of the brush is 3.0 ft, and the average height of the willow is 10 ft. The percentage of cross-section area of flow that is blocked by each vegetation type is about 30 percent (table 10). These component values are in the range of data used to develop the relation in this report.

Table 10. Channel and vegetation components for the example case

Vegetation type	Median diameter d_{50}, in feet	Average vegetation height, in feet	Amount of flow blocked by vegetation, in percent	Vegetation distribution	Vegetation-flexibility factor, in foot pounds
Brush	0.3	3	30	Random	8.85
Willow	.3	10	30	Random	63.2

Use of the relation (fig. 9) presented in this report to estimate the effect of flow on vegetation conditions requires quantification of the stream power as well as the vegetation-susceptibility index. Information obtained from a detailed description of the channel and vegetation conditions in the reach as well as a survey of the study reach can be used to compute the vegetation-susceptibility index. For the hydraulic computations, the standard-step method (Shearman, 1990) is used. This method requires solution of the energy equation, continuity equation, and Manning's equation. Components required to compute stream power are obtained from the standard-step computational results.

A stepwise procedure is suggested for using the information presented in this report. For the purposes of this example case, discharges that correspond to the 2-, 10-, 50-, and 100-year flows will be used. The magnitude of these discharges were determined arbitrarily (table 11).

Table 11. Frequency, probability, and discharge of instantaneous peak flow for the example case

Frequency	Probability of occurrence in a given year, in percent	Discharge, in cubic feet per second
2 year	50	1,000
10 year	10	5,000
50 year	2	13,000
100 year	1	24,000

The following steps will be used for the example case to illustrate use of the information presented in this report. These steps should also be followed by all users of this method.

STEP 1. Survey the channel to obtain parameters necessary for standard-step computations. For step 1a, in the estimation of roughness coefficients, fully weight the preflow-vegetation conditions for the selected discharge. For subsequent steps, use engineering judgment for estimating roughness coefficients.

Step 1a

The 2-year flow is initially selected. According to standard guidelines (Thomsen and Hjalmarson, 1991; and Phillips and Ingersoll, 1998) a composite n value of 0.070 ($n_b = 0.030$ and $n_4 = 0.040$) is determined (table 12). Go to **STEP 2.**

Step 1b

Although n may vary with depth, a composite n value of 0.070 is selected for the 10-year flow. Go to **STEP 2 (Step 2b).**

Step 1c

Because it was determined that the brush will be laid over as a result of the 10-year flow, n_4 for the brush will be considered negligible for step 1c. The flow-retarding effects associated with willow, however, are still included for step 1c. Because the values for willow plot near the vegetation-susceptibility threshold (fig. 11), the vegetation component for willow will need adjusting (decreased) for possible streamlining of the vegetation. In other words, the effect of the 10-year flow on willow may not be significant but it may cause minor branches to bend in the direction of flow. Consequently, on the basis of engineering judgement, for the 50-year flow, a composite n value of 0.050 ($n_b = 0.030$ and $n_4 = 0.020$) is determined. The bed-material component, n_b, may decrease as flow depth increases. For the purposes of this example, however, n_b will remain constant. Go to **STEP 2 (Step 2c).**

STEP 2. Run standard-step computations using the surveyed channel parameters and selected roughness coefficients. From the computations, obtain hydraulic radius, average velocity, and water-surface slope for the selected cross section.

Step 2a

For the 2-year flow, these values are 2.0 ft, 2.6 ft/s, and 0.0055 ft/ft for hydraulic radius, average velocity, and water-surface slope, respectively (table 12). Go to **STEP 3.**

Step 2b

For the 10-year flow, the values for hydraulic radius, average velocity, and water-surface slope are 5.5 ft, 5.1 ft/s, and 0.0066 ft/ft, respectively (table 12). Go to **STEP 3 (Step 3b).**

Step 2c

For the 50-year flow, the values for hydraulic radius, average velocity, and water-surface slope are 8.0 ft, 8.9 ft/s, and 0.0063 ft/ft, respectively (table 12). Go to **STEP 3 (Step 3c).**

STEP 3. Using the type and average height of vegetation in the selected cross section, determine the vegetation-flexibility factor, V_{flex}, for each vegetation type using equations found in table 3.

Table 12. Channel, hydraulic, and vegetation components

[*n*, Manning's roughness coefficient; ft, foot; ft/s, foot per second; ft/ft, foot per foot; ft-lb/s/ft^2, foot pounds per second per foot squared; ft-lb, foot pound; ---, not applicable]

Flood frequency	Manning's *n*	Hydraulic radius[1] (ft)	Average velocity[1] (ft/s)	Slope of water-surface profile[1] (ft/ft)	Stream power (ft-lb/s/ft^2)	Ratio of hydraulic radius to average vegetation height		Vegetation-susceptibility index (k_v) (ft-lb)	
						Brush	Willow	Brush	Willow
2 year	0.070	2.0	2.6	0.0055	1.78	0.7	0.2	177	15,200
10 year	.070	5.5	5.1	.0066	11.6	1.8	.6	35.4	5,060
50 year	.050	8.0	8.9	.0063	28.0	---	.8	---	1,260

[1]Obtained from standard-step computations (Shearman, 1990).

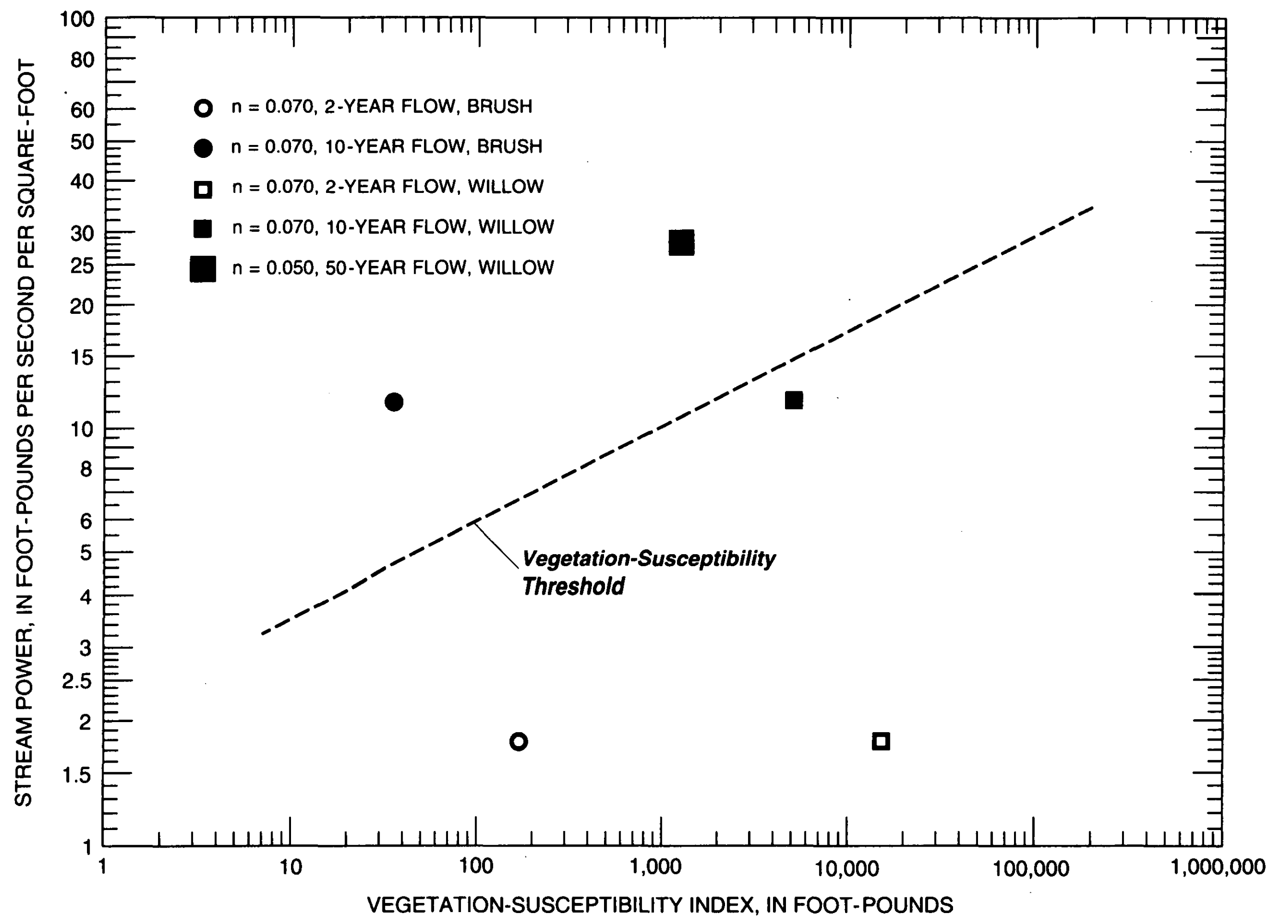

Figure 11. Effect of the 2-year and 10-year flow on brush and willow for roughness coefficient (*n*) equal to 0.070. Also shown is the effect of the 50-year flow on willow for *n* equal to 0.050.

Step 3a

V_{flex} values are 8.85 ft-lb and 63.2 ft-lb for the brush and willow, respectively, for all flows (table 10). Go to **STEP 4**.

Step 3b

V_{flex} values remain constant for all flows. Go to **STEP 4 (Step 4b)**.

Step 3c

V_{flex} values remain constant for all flows. Go to **STEP 4 (Step 4c)**.

STEP 4. Determine the orientation of the vegetation (either oriented randomly or parallel to flow) as well as the cross-section area of flow blocked by vegetation, and the ratio of hydraulic radius to average vegetation height for the selected discharge. Determine the vegetation-blocking coefficient, $C_{blocking}$, the vegetation-distribution coefficient, C_{dist}, and the flow-depth coefficient, C_{depth} (tables 4, 5, and 6).

Step 4a

$C_{blocking}$ is equal to 4.0 for both vegetation types, C_{dist} is equal to 1.0 for both vegetation types and, for the 2-year flow, C_{depth} is equal to 5 and 60 for the brush and willow, respectively. Go to **STEP 5**.

Step 4b

$C_{blocking}$ and C_{dist} values remain constant. For the 10-year flow, however, C_{depth} is equal to 1.0 and 20 for the brush and willow, respectively. Go to **STEP 5 (Step 5b)**.

Step 4c

$C_{blocking}$ and C_{dist} values are assumed to remain constant for willow. For the 50-year flow, however, C_{depth} is equal to 5.0 for willow. Go to **STEP 5 (Step 5c)**.

STEP 5. Compute the vegetation-susceptibility index for the selected discharge using equation 3.

Step 5a

For the 2-year flow, the vegetation-susceptibility indices are 177 ft-lb and 15,200 ft-lb for the brush and willow, respectively (table 12). Go to **STEP 6**.

Step 5b

For the 10-year flow, the vegetation-susceptibility indices are 35.4 ft-lb and 5,060 ft-lb for the brush and willow, respectively (table 12). Go to **STEP 6 (Step 6b)**.

Step 5c

For the 50-year flow, the vegetation-susceptibility index is 1,260 ft-lb for willow (table 12). Go to **STEP 6 (Step 6c)**.

STEP 6. Compute stream power for the selected discharge using equation 1.

Step 6a

For the 2-year flow, computed stream power is 1.78 ft-lb/s/ft^2 (table 12). Go to **STEP 7**.

Step 6b

For the 10-year flow, computed stream power is 11.6 ft-lb/s/ft^2 (table 12). Go to **STEP 7 (Step 7b)**.

Step 6c

For the 50-year flow, computed stream power is 28.0 ft-lb/s/ft^2 (table 12). Go to **STEP 7 (Step 7c)**.

STEP 7. Plot the values for the vegetation-susceptibility index and stream power for each type of vegetation present in the channel (figure 9). If the values plot below the vegetation-susceptibility threshold, repeat steps 1 through 6 using the next largest discharge. If the values plot above the threshold, no further steps are required.

Step 7a

The power associated with the 2-year flow is not substantial enough to significantly affect either the brush or the willow (fig. 11). Go back to **STEP 1** using the 10-year flow (step 1b).

Step 7b

Plotting position for the brush now indicates that it probably will be laid over as a result of the 10-year flow. The willow, however, plots just below the vegetation-susceptibility threshold, and the effect of flow on it is questionable (fig. 11). Consequently, computations are made again but now only the effect of flow on the willow is evaluated. Go back to **STEP 1** using the 50-year flow (step 1c).

Step 7c

As indicated by the plotted position of willow, there is a high probability that it will be laid over as a consequence of the 50-year flow (fig. 11). At this discharge, the flow-retarding effects associated with the brush and willow will diminish greatly, and depending on the amount of proneness, the retarding effects associated with the vegetation may become negligible. No further steps are required.

Because it was determined that a 50-year flow is adequate to lay over vegetation growing in this channel, it is assumed that the vegetation will be laid over on the rising limb of the hydrograph for the 100-year flow. The resultant effect would be a dynamic decrease of flow resistance and increase in channel conveyance compared to conveyance computations made on the basis of preflow-vegetation conditions.

For determination of the water-surface elevations of the 100-year flow in this example case, selection of Manning's n should only account for the flow-retarding effects associated with the bed material and any residual effects of laid-over vegetation. Because the residual effects were considered minor, for this example, a Manning's n of 0.035 would be recommended for design-discharge computations for the 100-year flow. The result is a substantial reduction in n compared to estimates made on the basis of preflow-vegetation conditions using current guidelines and techniques. By comparing computed water-surface elevations for n values equal to 0.035 and 0.070, the potential error in water-surface elevation computations resulting from incorrect assessment of peak-flow vegetation conditions for this example case for the 100-year flow is 3.58 ft. As discussed previously in this report, a sufficient amount of information was not available in this study to develop a substantive relation for the removal of vegetation and, therefore, the removal of the vegetation for the example case was not considered.

ASSUMPTIONS AND LIMITATIONS

Although not documented in this study, the possibility of laid-over vegetation springing back to an upright position when the power and forces of flow subside is a concern. An assumption required for analysis of data gathered for this report demands that the flow-affected vegetation remain in a position following flow similar to that during peak flow. For example, if vegetation was laid over during peak flow, it is assumed to remain in this position when flow subsides. Additionally, caution should be taken when transferring the results from this study to other sites especially if the channel and vegetation conditions of the other sites are substantially different from the channel and vegetation conditions used to derive the relation in this report.

For the simple semiempirical relation presented in this report (fig. 9), stream power was used to describe the flow-induced changes to vegetation; however, some important inherent uncertainties exist. For example, peak-flow velocity was required for use in the stream-power equation, and barring a direct current-meter measurement, peak-flow velocities were primarily obtained by use of Manning's equation. Estimates of peak-flow n values made after the flow subsided were based on the assumption that any noticeable change in roughness elements (vegetation for example) occurred before peak flow, and postflow-vegetation conditions were assumed identical to those at peak flow. This assumption may be inaccurate under certain conditions and could lead to errors in computations of peak-flow velocity and subsequent calculations of stream power.

SUMMARY

This report presents data and describes methods that are intended to aid water-resource managers and engineers in the process of assessing peak-flow resistance in vegetated channels. The semiempirical relation presented can be used to estimate the effects of flow on main-channel vegetation conditions and consequent effects on computations of channel-conveyance and water-surface elevations. The relation is presented for the purpose of mitigating possible gross errors in these conveyance computations.

The data and relation presented in this report can be used for a wide range of hydraulic applications that require assessment of channel and vegetation conditions during peak flow. Potential applications include postflow-discharge determinations (indirect measurements), standard-step computations to delineate flood-plain boundaries, and capacity computations for hydraulic structures. Although transferable to sites with similar channel and vegetation conditions, the information presented in this report should only be applied on the basis of sound engineering judgment. The high degree of variability in channel and vegetation conditions may not be properly accounted for by the simple approach and methods set forth in this investigation. The most applicable and accurate transfer of results would be to vegetation growing in the main channel of trapezoidal, uniform reaches such as constructed channels in urban areas. Further research may result in development of a substantive relation that can reliably predict the shear stresses associated with vegetation removal.

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BASIC DATA

Table 13. Physical characteristics of willow, palo verde, saltcedar, and mesquite in streams in central Arizona

[ft, foot; lb, pound; ft-lb, foot pound]

Height of vegetation (ft)	Base circumference (ft)	Force (lb)	Moment arm (ft)	Moment (ft-lb)	Moment arm divided by height of vegetation	Base circumference of vegetation divided by height of vegetation
			Willow			
4	0.20	4.0	2	8.0	0.5	0.05
4	.25	6.0	2	12	.5	.06
6	.25	10	2	20	.3	.04
7	.30	13	3	39	.4	.04
8	.30	14	3	42	.4	.04
10	.40	16	4	64	.4	.04
15	.60	49	6	294	.4	.04
16	.50	36	6	216	.4	.03
16	.70	47	6	282	.4	.04
16	.90	73	6	438	.4	.06
16	1.00	82	6	492	.4	.06
17	.80	76	6	456	.4	.05
17	1.10	70	6	420	.4	.06
17	1.10	78	6	468	.4	.06
18	.80	94	6	564	.3	.04
			Palo verde			
3	.20	13	2	26	.7	.07
4	.20	15	2	30	.5	.05
5	.20	13	2	26	.4	.04
5	.20	50	2	100	.4	.04
6	.30	22	3	66	.5	.05
6	.30	24	3	72	.5	.05
7	.30	60	2	120	.3	.04
8	.60	96	3	288	.4	.08
8	.40	32	4	128	.5	.05
9	.40	48	4	192	.4	.04
9	.90	140	4	560	.4	.10
10	.50	76	4	304	.4	.05
10	.60	95	4	380	.4	.06
11	.70	90	4	360	.4	.06
12	1.40	170	5	850	.4	.12
			Saltcedar			
6	.20	13	2	26	.3	.03
7	.25	17	3	51	.4	.04
9	.30	20	4	80	.4	.03
11	.30	24	4	96	.4	.03
13	.30	22	5	110	.4	.02
14	.40	23	5	115	.4	.03
14	.40	35	5	175	.4	.03
15	.50	53	5	265	.3	.03
15	.60	95	4	380	.3	.04
16	.60	93	5	465	.3	.04
			Mesquite			
5	.25	20	2	40	.4	.05
6	.20	26	2	52	.3	.03
7	.30	27	3	81	.4	.04
12	.30	26	3	78	.2	.02
13	.70	162	4	648	.3	.05
14	.50	94	4	376	.3	.04
16	.50	161	6	966	.4	.03
17	.90	290	5	1,450	.3	.05
18	1.10	230	7	1,610	.4	.06

Figure 12. View from New River Road crossing looking upstream before the flow of January 8, 1993, Cave Creek above New River Road (site 7).

Figure 13. View from New River Road crossing looking upstream after the flow of January 8, 1993, Cave Creek above New River Road (site 7). Road crossing was washed out as a result of significant bedload transport during the flow.

Figure 14. Looking upstream from left bank during the flow of March 1, 1991, Skunk Creek above Interstate 17 (site 2).

Figure 15. Looking upstream from midchannel after the flow of September 28, 1995, Skunk Creek above Interstate 17 (site 2).

Figure 16. View from left bank of channel looking upstream before the flow of February 15, 1995, Hassayampa River near Wickenburg (site 9).

Figure 17. View from left bank of channel looking upstream after the flow of February 15, 1995, Hassayampa River near Wickenburg (site 9).

Figure 18. View from right bank looking upstream before the flow of February 15, 1995, Hassayampa River near Arlington (site 5).

Figure 19. View from right bank looking upstream after the flow of February 15, 1995, Hassayampa River near Arlington (site 5).

Figure 20. Looking downstream from midchannel before the flow of December 10, 1991, Agua Fria River tributary near Youngtown (site 13).

Figure 21. Looking upstream from left bank during the flow of December 10, 1991, Agua Fria River tributary near Youngtown (site 13). Vegetation was unaffected by flow and resulted in a significant backwater effect and road closure.

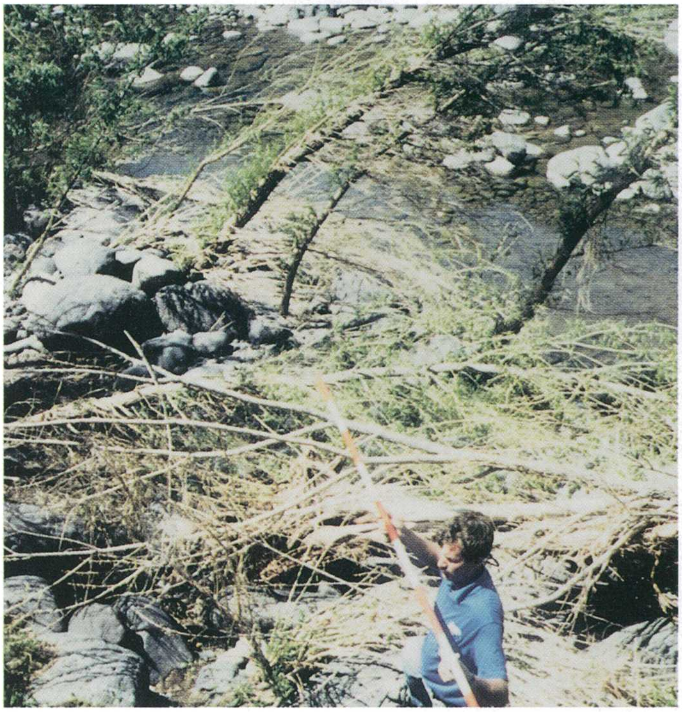

Figure 22. View from right bank looking toward laid-over willow in the main channel after the flow of January 8, 1993, Francis Creek near Bagdad (site 10).

Figure 23. Looking across the channel from left bank toward several laid-over willows after the flow of January 8, 1993, Francis Creek near Bagdad (site 10).

Figure 24. Looking upstream from left bank before the flow of January 8, 1993, New River above Interstate 17 (site 8).

Figure 25. Looking upstream from left bank after the flow of January 8, 1993, New River above Interstate 17 (site 8).

Figure 26. Looking upstream from right bank before the flow of January 8, 1993, Verde River near Scottsdale (site 1).

Figure 27. Looking upstream from right bank after the flow of January 8, 1993, Verde River near Scottsdale (site 1). Vegetation on left bank was substantially affected by flow.

Figure 28. Looking upstream from midchannel before the flow of January 8, 1993, New River above New River Road (site 16).

Figure 29. Looking upstream from midchannel after the flow of January 8, 1993, New River above New River Road (site 16).

Figure 30. Looking upstream from midchannel at laid-over brush after the flow of January 8, 1993, Salt River above Interstate 10 (site 6). The square reference (painted orange) has an outside dimension of 1.5 feet.

Figure 31. Looking upstream from left bank at willow after the flow of January 8, 1993, Salt River above Interstate 10 (site 6).

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