Iowa Design Manual for Low Water Stream Crossings

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ABSTRACT

Most counties have bridges that are no longer adequate and, therefore, are faced with a large capital expenditure if the same type replacement structure is proposed. Because a low water stream crossing (LWSC) may be an attractive low-cost alternative to replacing a costly bridge, a manual has been developed to design LWSCs for use in Iowa. The purpose of the manual is to provide consistent guidelines for county engineers and consultants designing these crossings. An LWSC is defined as an unvented ford, a vented ford (one having some number of pipes), a low water bridge, or other structure that is designed so that its hydraulic capacity will be insufficient one or more times during a year of normal rainfall. The use of unvented fords is discouraged in Iowa, and locations where vented fords are permissible have been narrowly defined. Because local social, economic, and political conditions vary from county to county, no hard and fast rules have been set down as to where LWSCs can be used; nevertheless, once the decision to use an LWSC has been made, the manual contains a simple design procedure for these crossings. This procedure includes the following phases: hydrology, hydraulics, roadway geometrics, and material selection. Discharges are estimated from equations that include drainage area, return period, and flow duration. Three methods are included to select the material used to protect the crossing from washing out, the first two of which are based on geomorphic relationships developed from Iowa stream gauging station records.

Most counties have bridges that are no longer adequate and, therefore, are faced with a large capital expenditure if the same size replacement structure is proposed. A low water stream crossing (LWSC) may be an attractive low cost alternative to replacing a costly bridge. The ideal situation would be to close the road but this alternative is not always available. However, if loss of access for a short time is not a problem, the site may be a candidate for an LWSC. In Iowa locations where LWSCs would be permitted have been narrowly defined.

One example would be on a primitive road serving only as a field access for local farmers. During good weather conditions, a well-designed vented ford would provide adequate facilities for any traffic using the road. During periods of significant rainfall, because the primitive or unpaved road is not passable except by farm equipment or four-wheel drive vehicles, the closing of the flooded LWSC is not a problem to the traveling public.

However, not all obsolete bridges are on primitive roads serving only as a field access. Other potential locations for LWSCs that may tolerate a short loss of access are those that have no:

- Residences with sole access over the LWSC,
- Critical school bus route,
- Recreation use, or
- Critical mail route.

If these uses do exist, the road may still be a potential candidate for an LWSC if an alternate route is available.

A survey of LWSC use in the United States by Carstens (1) indicated that 61 percent of the respondents used LWSCs only on unpaved roads. Because paved highways have geometric design and traffic control conducive to higher speeds, drivers' expectations are not consistent with the vertical profile encountered at LWSCs. Also, because unpaved roads are limited to low traffic volumes, the use of LWSCs on these roads would involve a lower exposure to traffic.

DEFINITION AND PURPOSE

An LWSC is a stream crossing that will be flooded periodically and closed to traffic. Carstens (1) had defined an LWSC as "a ford, vented ford (one having some number of culvert pipes), low water bridge, or other structure that is designed so that its hydraulic capacity will be insufficient one or more times during a year of normal rainfall."

The purpose of the Iowa manual (2) is to provide design guidelines for LWSCs, after it has been determined that an LWSC is applicable at a certain location. Because conditions vary from county to county, rigid criteria for determining the applicability of an LWSC to a given site are not established nor is a "cook-book" procedure for designing an LWSC presented.

COMPONENTS

An LWSC consists of several components: core material(s); foreslope surface; roadway surface; pipes (if it is a vented ford); and cutoff walls or riprap for protection against stream erosion. The core can consist of earth, sand, gravel, riprap, concrete, or a combination of these materials. Erosion protection for the foreslopes can consist of turf, riprap, soil cement, gabions, or concrete. The roadway surface can be composed of similar materials with the provision that a suitable riding surface be provided. The cost and availability of these materials vary from county to county; therefore, the exact composition of the core and surfacing will depend on local conditions. Pipes can be circular, oval, or arch and made of concrete, corrugated metal, or polyvinylchloride (PVC).

Protection against stream erosion can be provided by either cutoff walls or by armoring the stream bed. Cutoff walls can be constructed of either concrete or steel. The armoring could be riprap or gabions. Again, whether steel, concrete, or rock is used will depend on local cost and availability of materials and machinery such as pile drivers.

DESIGN CONCEPTS AND CRITERIA

The following criteria and design steps are unique to Iowa conditions and concepts as to what constitutes a well-designed LWSC. Much of this may be applicable to other states as well but each item should be construed as only a guideline because each site is unique and each county has its own unique set of conditions.

General Criteria

1. Based on the study by Carstens (1), with the adoption of the recommended regulatory sign and support resolution, the road will be closed when water is flowing across it. Because of this, for vented fords the headwater elevation for the selected overtopping frequency and estimated discharge must be at, or slightly below, the low point in the roadway.
2. This overtopping discharge is based on the concept that the crossing will be closed a certain percent of the time. Because each site is unique and the decision on overtopping duration must be based on the existing physical, social, economic, and political factors present for that site and county, only general guidelines are given for the allowable overtopping frequency.
3. The assumption is made that the existing channel cross section is not altered; that is, its width is not increased so that more pipes can be laid in the widened channel. However, the channel banks could be cut down to allow for proper approach grades.
4. The minimum depth of cover over the pipes in a vented ford is 1 foot.
5. Road grades, vertical curve lengths, and rideability reflect the low speeds allowed on these roads.
6. Flows overtopping the crossing should be controlled to minimize erosion so that damage is low and repair is easy. This can be done by keeping the difference between the upstream and downstream water surfaces to a minimum. One way to achieve this is to keep the difference between the low point in the roadway and the stream bed to a minimum.
7. Because alternative types of materials can be used in the construction of an LWSC, the availability and cost of these materials in different counties could lead to different decisions between these counties.
8. Based on the study by Carstens (1), suitable signing reduces the liability.
9. The type of material used to protect the LWSC from erosion could be influenced by the size and location of the county's maintenance force and the number of LWSCs in the county. Some crossings may need to be inspected after a flood event for needed maintenance. This maintenance could range from sediment and debris removal to major repairs. The time lapse between the flood event and the road being reopened could be excessive if the number of LWSCs requiring significant maintenance is large and the maintenance force is small and located some distance away. How long a period of time is excessive is dependent on the site and the county's social and political climate.

Steps in Design

The general steps involved in the design of an LWSC are discussed briefly in the following paragraphs. The location in Iowa is needed to determine in which hydrologic region the LWSC is located. The watershed size is measured in square miles. These two items are used to estimate discharges and to select crossing materials.

Most LWSCs will be vented fords. Because of the safety problems of driving through water, unvented fords could be closed much of the time and should be used only on those intermittent streams that are dry for the percent of time compatible with the uses of the road.

The allowable overtopping duration is a function of the several items discussed earlier. Because each site is unique, the decision on the duration of overtopping must be based on the existing physical, social, economic, and political factors for that site and county. After this decision is made, the overtopping discharge then can be estimated using equations developed by the U.S. Geological Survey (USGS) for Iowa.

Using the overtopping discharge and the criteria listed in the previous section, the number and size of pipes as well as the headwater depth can be determined from Herr and Bossy (3), commonly known as HEC-5 or Bulletin 5. The pipe can be circular, oval, or arch and made of concrete, corrugated metal, or PVC. Each of these pipe shapes and materials is analyzed using HEC-5 under both inlet and outlet control.

The crossing grades and elevations are a function of the overtopping discharge headwater depth and the physical characteristics of the existing channel and roadway. For vented fords, the low point in the roadway should be in the range of 2 to 6 ft above the stream bed, depending on the size of pipes, depth of cover over the pipes, roadway and surfacing material used, and depth of channel.

Two criteria must be met: (a) the headwater depth for the number and size of pipes selected must be at or slightly below the low point in the roadway and (b) the grades and length of the crest and sag vertical curves must meet the stopping sight distance criterion. The possibility exists that in order to meet criterion b, the low point in the roadway has to be raised above the elevation needed for either the calculated headwater depth or minimum cover criteria. In this case, the possibility exists that the number and size of pipes could be reduced.

Material selection for the crossing foreslopes and roadway surface is a function of the channel velocity and tractive force. High flows (Q_{10} to Q_{50}) will usually govern except for large differences between headwater and tailwater depth when the velocity of the overtopping discharge ($Q_{50\%}$ to $Q_{1\%}$) plunging down the downstream foreslope could be the governing case. These materials can range from turf to concrete.

Other considerations include provisions to protect against stream erosion and seepage. This could consist of steel or concrete cutoff walls or riprap blankets.

DESIGN OF A VENTED FORD

Step 1. Region and Drainage Area

Figure 1 shows the locations of the three hydrologic regions in Iowa. For smaller watersheds, the drainage area can be determined from a 7.5- or 15-minute quadrangle map. For watersheds larger than 5 square miles, Bulletin No. 7 by Larimer (4) can be used to determine the drainage area in Iowa.

Step 2. Flow-Duration Estimates

A flow-duration curve indicates the percent of time within a certain period in which given rates of flow

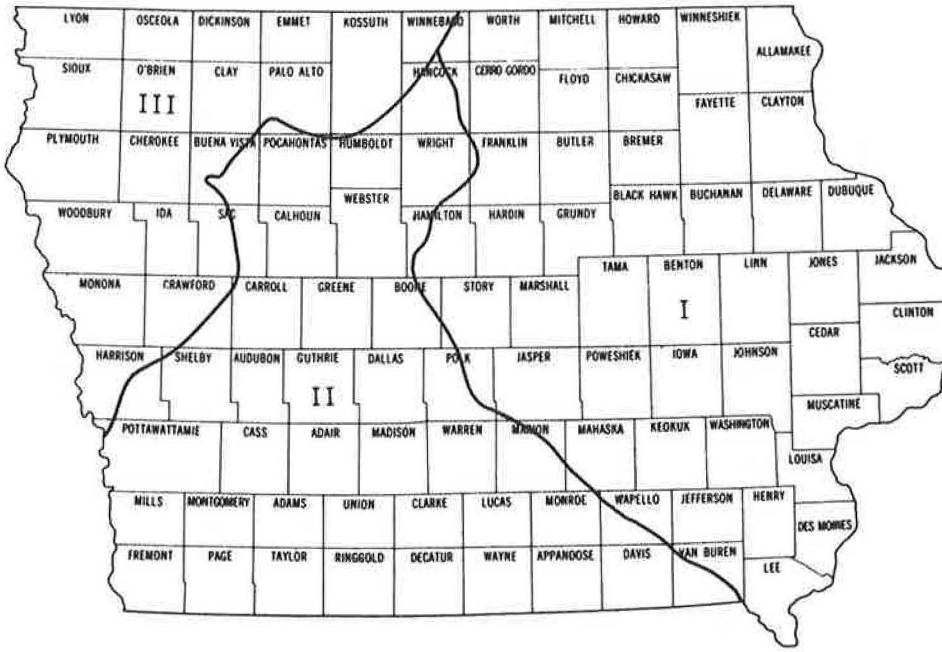

FIGURE 1 Hydrologic regions for duration of discharge equations.

were equaled or exceeded. Flow-duration data for daily flows collected at all the gauging stations in Iowa can be found in Lara (5). These data are used to prepare flow-duration curves at the gauging stations. More frequently, flow-duration information is needed at stream crossings where no recorded data are available. The following procedure can be used to estimate flow-duration information for ungauged sites:

1. Using the map in Figure 1, identify the hydrologic region where the project site is located.
2. Determine the size of the drainage area at the site in square miles.
3. Select a value of e, based on site and county conditions, and the corresponding regression coefficients from Table 1, then solve the following equation.

$$Q_e = aA^b \tag{1}$$

where

Q = discharge in ft³ per second (cfs),
e = exceedance probability in percent,
A = drainage area in square miles, and
a and b = regression coefficients. (Values of a and b are listed in Table 1 for each hydrologic region shown in Figure 1.)

TABLE 1 Regional Regression Coefficients for Estimating Duration of Flows Having the Indicated Exceedance Probability

Exceedance Probability e, %	Region I a	Region I b	Region II a	Region II b	Region III a	Region III b
50	0.17	1.05	0.06	1.09	0.015	1.24
25	0.52	1.01	0.24	1.06	0.04	1.25
10	1.37	0.98	0.91	1.00	0.15	1.19
5	2.58	0.96	2.26	0.95	0.33	1.15
2	6.78	0.90	6.78	0.90	1.23	1.06
1	13.50	0.85	13.50	0.85	3.56	0.96

Equation 1 and Table 1 are the results of regression analyses performed on the data contained in Lara (5).

Using this equation with Table 1 yields the following results for a 6-square mile watershed in Dallas County, Iowa.

$$Q_{25\%} = 0.24(6)^{1.06} = 1.6 \text{ cfs} \tag{2}$$

$$Q_{2\%} = 6.78(6)^{0.90} = 34.0 \text{ cfs} \tag{3}$$

These discharges are interpreted as follows. If the LWSC is designed for $Q_{25\%}$, the crossing will be closed an average of 3 months each year. If the LWSC is designed for $Q_{2\%}$, the crossing will be closed an average of 7 days each year. Similar equations for other states could be derived using the same methodology employed by the USGS in Iowa.

Step 3. Stage-Discharge Curves

A stage-discharge curve for a channel section is developed by assuming increasing values of depth, determining the discharges by multiplying the cross-sectional area of flow at each depth by the average velocity of flow obtained from Manning's equation at each depth, then plotting depth versus discharge with depth as the ordinate.

The channel cross section and slope (low water surface profile) at the site are measured in the field. Field observations also are made to allow estimation of the roughness coefficient. Calculations for area and wetted perimeter are made by plotting the channel cross section as a series of straight lines, then using simple geometric shapes.

Step 4. Number and Size of Pipes

Determining the number and size of pipes for a particular site is a trial and error process. Several items must be kept in mind:

1. The total width of pipes, including the spaces between them, must be less than the width of the existing channel;

2. The headwater depth controls the low point in the roadway;

3. The pipes can operate under either inlet or outlet control;

4. Pipe lengths are short, but differences in friction losses due to pipe material can still be significant;

5. A large difference between the low point in the roadway and the downstream water surface increases the erosion potential on the downstream foreslope; and

6. A large difference between the low point in the roadway and the stream bed increases the volume of material needed in the crossing and thus increases its cost.

The trial and error process begins by determining headwater depths for the estimated overtopping discharge and assumed combinations of pipe material, number, and size operating under inlet control. The results are reviewed in light of the preceding items and the several combinations reduced to the few best alternatives. These alternatives are checked for outlet control, using the stage-discharge curve developed in the previous step, and the final type, size, and number of pipes selected. These headwater depths for both inlet and outlet control are determined from charts contained in Herr and Bossy (3).

ROADWAY GEOMETRICS

Crossing Profile

General Concepts

Low water stream crossings are designed for occasional overtopping with floodwater and, consequently, have an inherent vertical dip characteristic. This sudden dip in the vertical alignment is not consistent with drivers' expectations of a public highway profile. Proper signing is essential to alert the driver to a condition that cannot be traversed at the higher speeds associated with tangent alignments and flat grades.

The variables of concern in the design of the stream crossing road profile are the tangent grades, the length of sag vertical curve, and crest vertical curve lengths at the stream edges.

Selecting Tangent Grades

The selection of tangent grade lines will be dependent on the height of the stream banks and the slope of the terrain adjacent to the stream banks, as well as the amount of cut allowed into the stream bank. If minimal grading is desired, steep grades will result. However, steep grades significantly increase the stopping distance. In general, a grade of 12 percent could provide a surface suitable for driving when wet and muddy, but only at very low speeds.

The use of flat grades that cause a cutback into the stream bank can result in a maintenance problem. When high water causes overtopping of the crossing, the flood water spreads onto these flat approach grades wider than the normal stream width, and subsequently deposits debris and mud on the crossing roadway.

Selecting the Length of Vertical Curves

A number of criteria are recognized in the design of a crossing profile. Stopping sight distance is the usual criterion for selecting the length of crest vertical curves, whereas headlight sight distance, driver comfort, and appearance may be used for sag vertical curve length determination.

Because of the reduced speed conditions and the inherent short space for crest vertical curves at the stream banks, the normal stopping sight distance criterion for selecting a length of vertical curve is the controlling factor, rather than comfortable ride. Stopping sight distance is applicable on the approaches, especially if obstructions in the horizontal alignment occur, which would restrict the view of the crossing.

Table 2 has been prepared based on the 1965 AASHO stopping sight distance formula. The coefficient of friction was assumed to be 0.20 due to slick conditions on unpaved roads and the grade was assumed to be 10 percent. These distances were then used in LWSC vertical curve calculations.

TABLE 2 Stopping Sight Distances for LWSCs

Vehicle, mph	Perception and Brake Reaction Distance, ft	Braking Distance, ft	Stopping Distance, ft
5	18.4	8.3	27
10	36.8	33.3	70
15	55.1	75.0	130
20	73.5	133.3	210
25	91.8	208.3	300
30	110.3	300.0	410

Crest Vertical Curves

Minimum crest vertical curve lengths were determined using a height of eye of 3.5 ft and a height of object of 6 in. For a given algebraic difference in grades, A, and a vertical curve length, L, selected to fit the terrain, designers generally use the reciprocal of the rate of change of grade, or $K = L/A$, as a measure of curvature in determining speeds for a given crest vertical curve design.

A common procedure for determining minimum length of crest vertical curves is to plot A and L for various speeds. Figure 2 is a design chart for selecting a length of LWSC crest vertical curve, or conversely, having selected a suitable length of vertical curve to fit the terrain, Figure 2 may be used to determine the speed for that design. The minimum vertical curve lengths in Figure 2 are based on a value of three times the speed in feet per second.

Sag Vertical Curves

In the design of a sag vertical curve for normal street and highway design practice, the concept of headlight sight distance determines the length of vertical curve. A suitable length of sag vertical curve allows the roadway ahead to be illuminated so that a vehicle could stop in accordance with the stopping sight distance criteria. For safety reasons, the light beam distance is set equal to the safe stopping distance.

Figure 3 shows the sag vertical curve design chart. It may be used to select the length of sag vertical curve for a specific set of grades and speed condition, or having selected a trial sag vertical curve, the speed associated with that design may be determined. The minimum values in Figure 3 are based on three times the speed in feet per second.

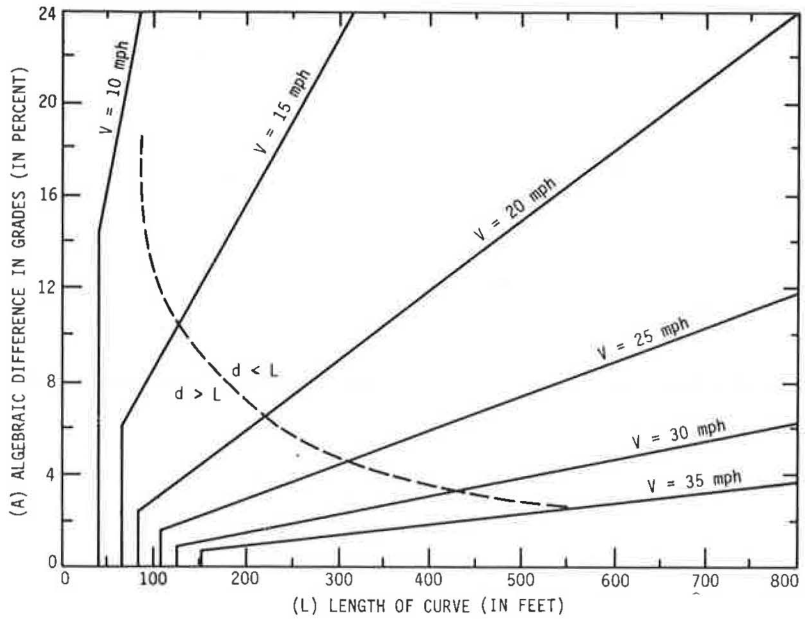

FIGURE 2 Minimum length of crest vertical curve for LWSCs.

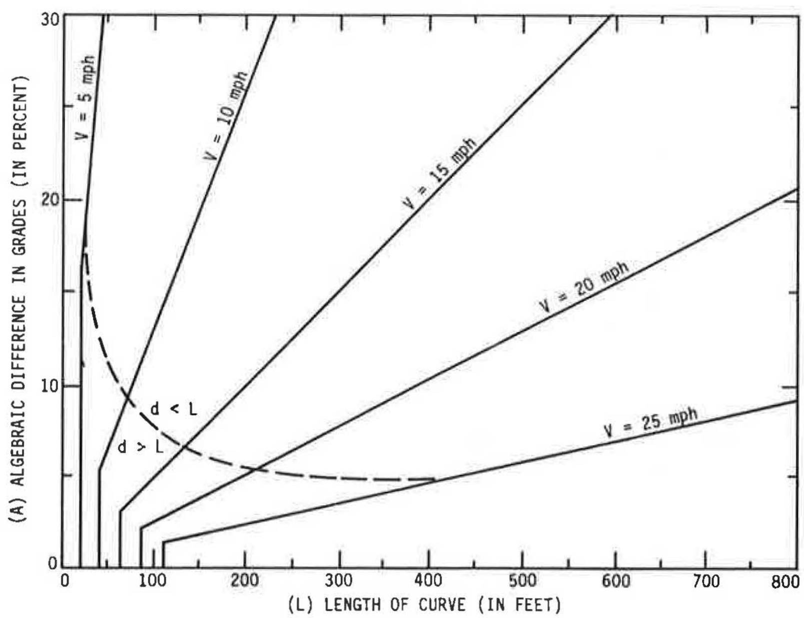

FIGURE 3 Minimum length of SAG vertical curve for LWSCs.

Cross Section

The function of the cross section is to accommodate vehicles on the roadway and to allow periodic higher stream flows to cross the roadway. Passenger vehicles are in the range of 6.0 to 6.5 ft wide, whereas pick-up trucks are in the range of 8 ft wide. Farm vehicles of much wider dimensions commonly use these types of roads and may legally do so. One of the advantages of an LWSC over a bridge, on a farm field access road, for example, is the unrestricted farm vehicle width that can be accommodated. Old bridges with guard rails on the approaches present problems for wide farm vehicles. Farm vehicles in common use have transport widths of 18 to 20 ft; some vehicles may reach 28 ft in transport width.

For design purposes, a 16-ft top width would be minimal, with a 20-ft or greater top width desirable. The roadway should be crowned to cause water to run off and reduce ponding on the roadway. As periodic overtopping of the roadway occurs, a crown of 0.02 ft per foot from the upstream side to the downstream side will tend to be more self-cleaning than a crown symmetrical about the centerline. Also, the pavement should have transverse grooves for traction.

Low water stream crossings have been constructed with vertical sides as well as with battered side slopes. Also, the pipes may protrude or be flush with the foreslopes of the cross section. The major disadvantage of a vertical foreslope is the debris-erosion problem. A 2:1 foreslope with smoothly trimmed pipes may be self-cleaning on the upstream side. Such a configuration provides a more hydraulically efficient design. The use of curtain walls on both the upstream and the downstream edges is common to reduce erosion and undercutting.

Traffic Control Signs

An LWSC has two unique characteristics not associated with a traditional bridge that may create a potential for accidents and subsequent liability claims. The vertical profile at the crossing is usually restricted to low speeds and the pavement surface is subject to periodic flooding. It is imperative that adequate warning of these conditions be transmitted to the user. The recommendations contained herein are based on the research by Carstens (1) and are shown in Figure 4.

The intent of the regulatory sign DO NOT ENTER WHEN FLOODED is to preclude travel across the LWSC when the roadway is covered with water. Such a regulatory sign requires a resolution by the Board of Supervisors. The adoption of this sign in effect precludes the use of an unvented ford.

SELECTION OF CROSSING MATERIALS

The surfacing material of any ford can be determined by using one of the three following methods that estimate a tractive force and velocity. Then these values can be compared with critical values for various materials. The first two methods rely on geomorphic relationships developed from flow gauging stations in Iowa. The first method presumes that the designer only has a knowledge of the size of the drainage area upstream of the proposed crossing site. Figures 5 and 6 are then used to relate watershed size to tractive force and velocity.

The recommended value that grass is capable of resisting is a velocity of 3 ft per second. Table 3 gives values of tractive force that different sizes of riprap are capable of resisting. Using Table 3, the engineer can select a riprap size that will be capable of resisting the τ_t values obtained from Figure 5. The tractive forces given correspond to the critical tractive force (τ_c), which the various sizes of riprap are capable of resisting. For values of velocity and tractive force greater than the values given previously, the engineer can use soil cement, gabions, fabriform, and portland cement concrete as construction materials. Considerations involved in the use of these materials are explained in the Iowa manual (2).

The second design method presumes that the engineer has detailed information about the channel's cross-sectional geometry in addition to knowing the watershed size. Using Figure 7, the designer can estimate a channel slope and depth of flow. The flow velocity can then be determined from Manning's

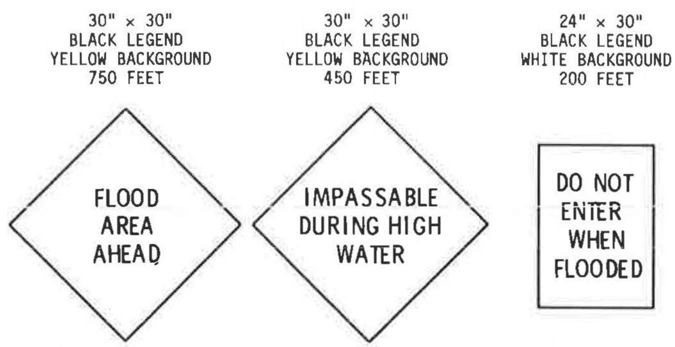

FIGURE 4 Signs recommended for installation at low water installations.

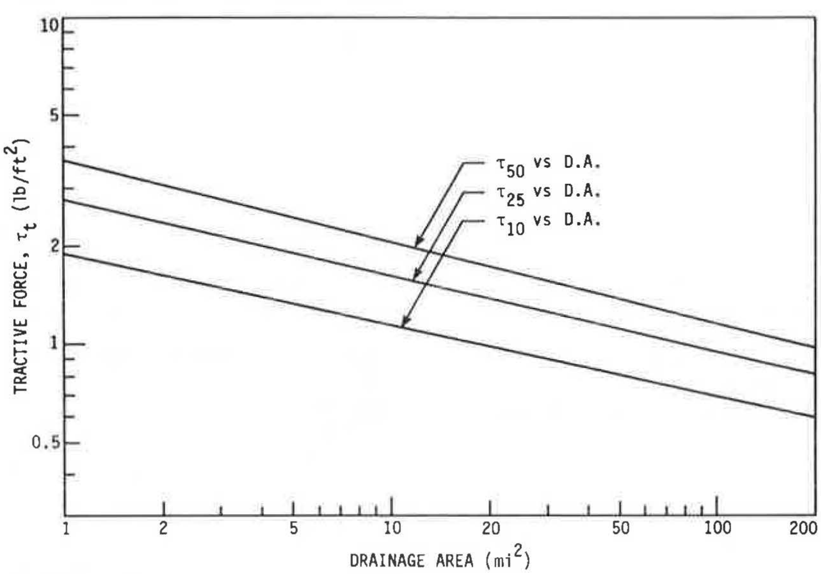

FIGURE 5 Tractive force (τ_t) versus drainage area.

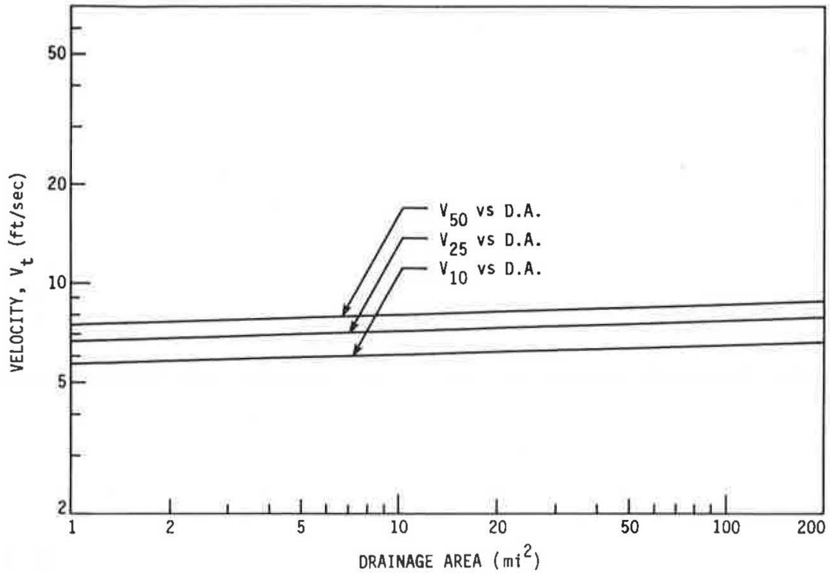

FIGURE 6 Velocity (V_t) versus drainage area, Region I.

TABLE 3 Critical Tractive Force Values for Different Sizes of Riprap

Material, in.	Critical Tractive Force, lb/ft^2
Riprap D_{50} = 6	2.0
Riprap D_{50} = 15	5.0
Riprap D_{50} = 27	7.3
Riprap D_{50} = 30	10.0

equation. The tractive force is calculated by using Equation 4.

$$\tau_t = 62.4Sd_t \quad (4)$$

where

τ_t = the tractive force in pounds per square foot for some return period, t;
S = the channel slope in feet per foot; and
d_t = the flow depth in feet for some return period, t.

The third method uses only physical data collected at the site: drainage area, channel cross section, channel slope, and valley cross section. The flow velocity and tractive force are determined as described in Method 2.

Using the values of V_t and τ_t calculated, suitable riprap can be selected by using Table 3 or other materials can be selected by considering the properties described in the Iowa manual (2). The designer can use one return period or, alternatively, can select values for all three return periods and determine the variation in construction material, if any, that results and use this information in the decision-making process.

SUMMARY

Most counties in the United States are faced with rising costs, stagnant or decreasing budgets, and an

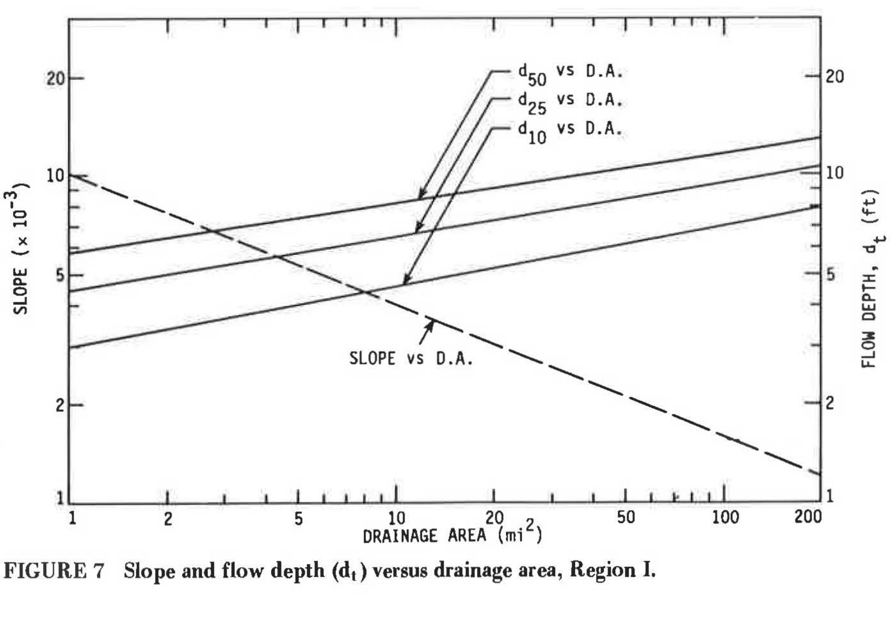

FIGURE 7 Slope and flow depth (d_t) versus drainage area, Region I.

increasing number of structurally and functionally obsolete bridges. Available funds must be stretched and new ways found to keep roads open. LWSCs are one method of replacing old bridges at a lower cost. However, because these low water crossings have an inherent dip in the road profile at the stream and because they are designed to be underwater several times a year, they present a possible hazard and must be properly designed and signed.

These design and signing aspects have been studied and the results presented in a design manual for LWSCs in Iowa. The types of crossings and locations where they may be used have been narrowly defined. In addition to the signing recommendations, the manual includes the hydrology, hydraulics, roadway geometrics, and material selection phases of the design process: estimates of flow for several overtopping durations are obtained from an equation developed by the USGS; the number and size of culverts for a vented ford are determined from a manual published by the Federal Highway Administration; considerations involved in the selection of road grades plus crest and sag vertical curve lengths are discussed; and three methods for designing protective materials to prevent erosion of the crossing are presented. The use of these guidelines and procedures should result in a well-designed and signed low water stream crossing.

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