Potential Drift Accumulation at Bridges

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16. Abstract

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The potential for drift accumulation depends on basin, channel, and bridge characteristics. Drift that accumulates at bridges comes primarily from trees undermined by bank erosion. Rivers with unstable channels have the most bank erosion and the most drift. Most drift floats along the thread of the stream. Logs longer than the width of the channel accumulate in jams, or are broken into shorter pieces.

Drift accumulates against obstacles such as bridge piers that divide the flow at the water surface. Groups of obstacles separated by narrow gaps trap drift most effectively. Drift accumulation begins at the water surface, but an accumulation may grow downward to the stream bed through accretion. A drift accumulation on a single pier grows no wider than the length of the longest logs it contains. The gap between two piers is not blocked by drift unless individual logs can reach from pier to pier. Design features to reduce the potential for drift accumulation include adequate freeboard, long spans, solid piers, round (rather than square) pier noses, and pier placement away from the path of drift.

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Conversion Table

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow	
feet per second (ft/s)	0.3048	meters per second (m/s)

Glossary

Accretion:	growth by gradual external addition of elements
Boom:	a series of connected floating units designed to deflect or contain floating material
Cofferdam:	a watertight enclosure pumped dry to allow construction below water level
Debris flow:	non-Newtonian flow of a dense, plastic mixture of soil, rock, water, and trees
Debris torrent:	debris flow occurring in a steep stream channel
FHWA:	Federal Highway Administration
Flood plain:	the area of a valley bottom outside the stream channel and covered by water during floods
Freeboard:	the distance between the water level and the lowest part of a bridge superstructure
Hydrostatic forces:	forces generated by the weight of standing water
Landslide:	gravity-driven movement of a mass of soil or rock
Lingulate bar:	mid-channel sediment bar with a gently rising upstream face and a steep downstream face
Low steel:	the lowest horizontal part of the bridge superstructure. When the water level is at or above low steel, the superstructure is partly immersed.
Point bar:	a sediment bar that forms along the base of the convex bank of a channel bend
Scroll bar:	a longitudinal sediment bar in the channel parallel to the convex bank of a channel bend
Thalweg:	the line of greatest depth along a stream channel
Thread:	the line of fastest flow at the water surface. The thread often, but not always, lies over the thalweg.
Trash rack:	a grating or series of pilings for retaining floating objects
USGS:	United States Geological Survey
Wind throw:	the uprooting of a tree by wind
WSPRO:	a one-dimensional, steady-flow step-backwater model containing specialized routines for bridge contractions, multiple openings, and supercritical-flow reaches.

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The potential for drift accumulation depends on basin, channel, and bridge characteristics. Drift that accumulates at bridges comes primarily from trees undermined by bank erosion. Rivers with unstable channels have the most bank erosion and the most drift. Most drift floats along the thread of the stream. Logs longer than the width of the channel accumulate in jams, or are broken into shorter pieces.

Drift accumulates against obstacles such as bridge piers that divide the flow at the water surface. Groups of obstacles separated by narrow gaps trap drift most effectively. Drift accumulation begins at the water surface, but an accumulation may grow downward to the stream bed through accretion. A drift accumulation on a single pier grows no wider than the length of the longest logs it contains. The gap between two piers is not blocked by drift unless individual logs can reach from pier to pier. Design features to reduce the potential for drift accumulation include adequate freeboard, long spans, solid piers, round (rather than square) pier noses, and pier placement away from the path of drift.

Introduction

Drift[1] accumulation at bridges is a widespread problem. Drift reduces the capacity of bridge openings, contributes to scour, and increases lateral forces on bridges. Drift contributes to more than one-third of the bridge failures in the United States and has been a primary cause of a number of failures (Chang, 1973). Current design guidelines treat drift as a threat to bridges, but do not include methods for estimating the size and likelihood of drift accumulations. Most published information regarding drift is anecdotal and qualitative. Such information is valuable, but difficult to apply in bridge design.

This report presents the results of a study of drift accumulation at bridges conducted by the U.S. Geological Survey (USGS), in cooperation with the Federal Highway Administration (FHWA). The study was conducted from 1992 through 1995, and included a review of published literature on drift, analysis of data from 2,577 reported drift accumulations, and field investigations of 144 drift accumulations.

The guidelines for the assessment of drift potential presented in this report summarize the main conclusions of this study in the form of a detailed drift-assessment method. The guidelines include methods for estimating the likelihood that drift will accumulate at a bridge and the maximum size of drift accumulations. These guidelines assign a relative potential for drift accumulation and do not estimate the probability of an accumulation occurring in a given year. Their use requires engineering judgement and some familiarity with regional drift characteristics.

Purpose and Scope

This report has two main purposes: (1) to provide a general description of drift characteristics and drift-related problems, and (2) to present an example of guidelines to assess the potential for drift accumulation at specific bridges, whether existing or under design.

The first component of the present study is a comprehensive review of the literature on drift and drift-related topics. The primary topics addressed in this literature review are:

- Studies of drift accumulation at bridges.
- Bridge design practices related to drift.
- Sources of drift.
- Drift transport.
- The amount and nature of drift stored in channels.
- Management of drift.
- Effects of drift at bridges.

Data collection for this study was international in geographic scope. Data were compiled for drift accumulations in 33 States and the District of Columbia; Puerto Rico; Manitoba and Saskatchewan; Malawi; and New Zealand (table 1). State Departments of Transportation in Indiana, Massachusetts, Maryland, South Carolina, and Tennessee cooperated with

[1] Drift is defined as “any type of debris that is floating on or through a river” (Pangallo and others, 1992). “Floating debris” is a synonymous term. In this report, the term “debris” is sometimes used in discussing previous studies that use this term for drift and refers to floating debris (Lagasse and others, 1991). However, “debris” is often used to refer to rocks transported by flowing water or dense, non-Newtonian mixtures of sediment and water, and the less ambiguous term “drift” is preferable (Perham, 1987).

Table 1. Sources of drift data by State.

[--, no data]

State, province, commonwealth, or country	Number of sites of drift accumulation from:				Total by State, province, commonwealth, or country
	Scour-potential studies	Reports from States	Field studies	Publications and communications	
Alabama	--	--	1	--	1
Alaska	--	--	--	7	7
Arizona	--	--	--	1	1
Arkansas	--	55	--	3	58
California	--	--	--	4	4
Delaware	--	1	--	--	1
Florida	--	2	--	--	2
Georgia	--	2	3	--	5
Idaho	--	2	--	1	3
Illinois	--	--	2	2	4
Indiana	270	--	12	8	290
Louisiana	--	--	--	12	12
Maryland	122	--	--	--	122
Massachusetts	54	--	13	--	67
Mississippi	--	--	2	2	4
Missouri	--	--	--	1	1
Nevada	--	--	--	2	2
New Mexico	--	23	--	--	23
New York	--	--	5	4	9
North Carolina	--	2	--	--	2
North Dakota	--	--	--	1	1
Ohio	--	--	--	1	1
Oklahoma	--	--	--	1	1
Oregon	--	3	--	1	4
Pennsylvania	--	3	--	10	13
South Carolina	1,053	--	--	--	1,053
South Dakota	--	--	--	6	6
Tennessee	802	--	66	4	872
Texas	--	--	12	11	23
Virginia	--	54	--	12	66
Washington	--	--	23	5	28
Wisconsin	--	8	4	--	12
Wyoming	--	--	--	1	1
District of Columbia	--	--	1	--	1
Puerto Rico	--	3	--	--	3
Manitoba	--	--	--	3	3
Saskatchewan	--	--	--	1	1
Malawi	--	--	--	1	1
New Zealand	--	--	--	13	13
TOTAL BY SOURCE	2,301	158	144	118	2,721

the USGS in potential-scour studies used as data sources in this study (figure 1). State Departments of Transportation in Arkansas, Delaware, Florida, Georgia, Idaho, New Mexico, North Carolina, Oregon, Pennsylvania, Virginia, and Wisconsin responded to a request for reports on drift accumulations (figure 2). Field studies were conducted in 11 States and the District of Columbia (figure 3). Data on accumulations in other States were obtained from publications and from written and oral communications (figure 4).

Several issues related to drift are outside the scope of this report:

- The cost of drift-related damage to bridges.
- The cost of drift removal.
- The cost of drift countermeasures.
- The appropriate balance between costs and risk.

Approach

Various methods were used to locate relevant publications. The literature search began with computer searches of the following databases:

- Compendex Plus from 1987 through 1992.
- Water Resource Abstracts from 1967 through 1992.
- Georef from 1792 through 1992.
- Life Sciences Collection from 1982 through 1992.

A citation search was performed for papers that cite a key paper on drift transport and jam formation (Likens and Bilby, 1982). Citations in articles obtained were examined for relevant material.

State Departments of Transportation were asked to provide reports on drift problems at bridges. A standard report form provided to them requested values for specific variables and solicited comments on several aspects of the site (figure 5). This form resembled that used by Chang and Shen, but contained additional data categories (Chang and Shen, 1979). Most reports were completed by district maintenance engineers or their staff. Photographs attached to several reports aided in data interpretation.

Several State Departments of Transportation, with support from the FHWA, have sponsored cooperative studies by the USGS of scour potential at bridges (Bryan and others, 1995; Huizinga and Waite, 1994). Compiled data were available from Indiana, Maryland, Massachusetts, Tennessee, and South Carolina (Noel Hurley, USGS, written commun., 1992; Ron Thompson, USGS, written commun., 1992; Bernard Helinsky, USGS, written commun., 1992; G.W. Parker, USGS, written commun., 1993). Data include size of drift accumulations; pier location, skew, and type; span length; channel width; and bank height. Other variables, including width of drift accumulations, percentage of channel blocked, effective span width, and ratio of drift width to span length, were calculated from the reported data.

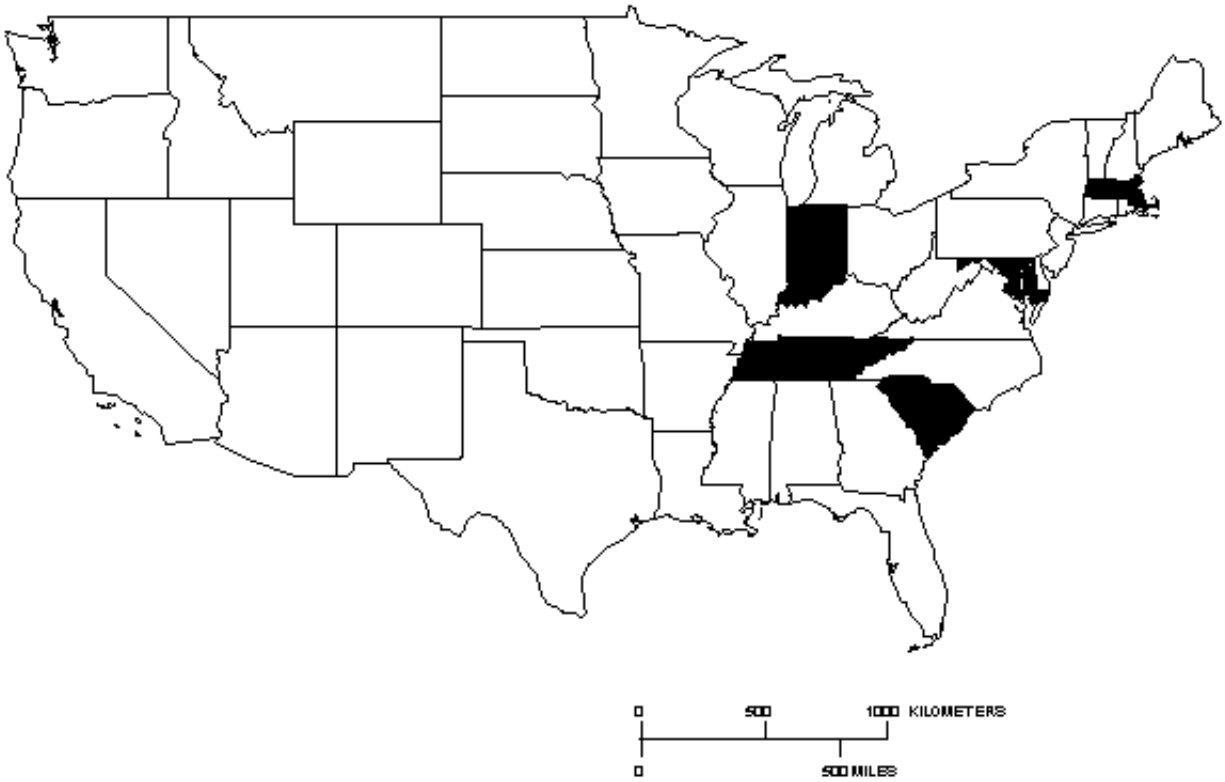

Figure 1. Map showing States with potential-scour study data used in this study.

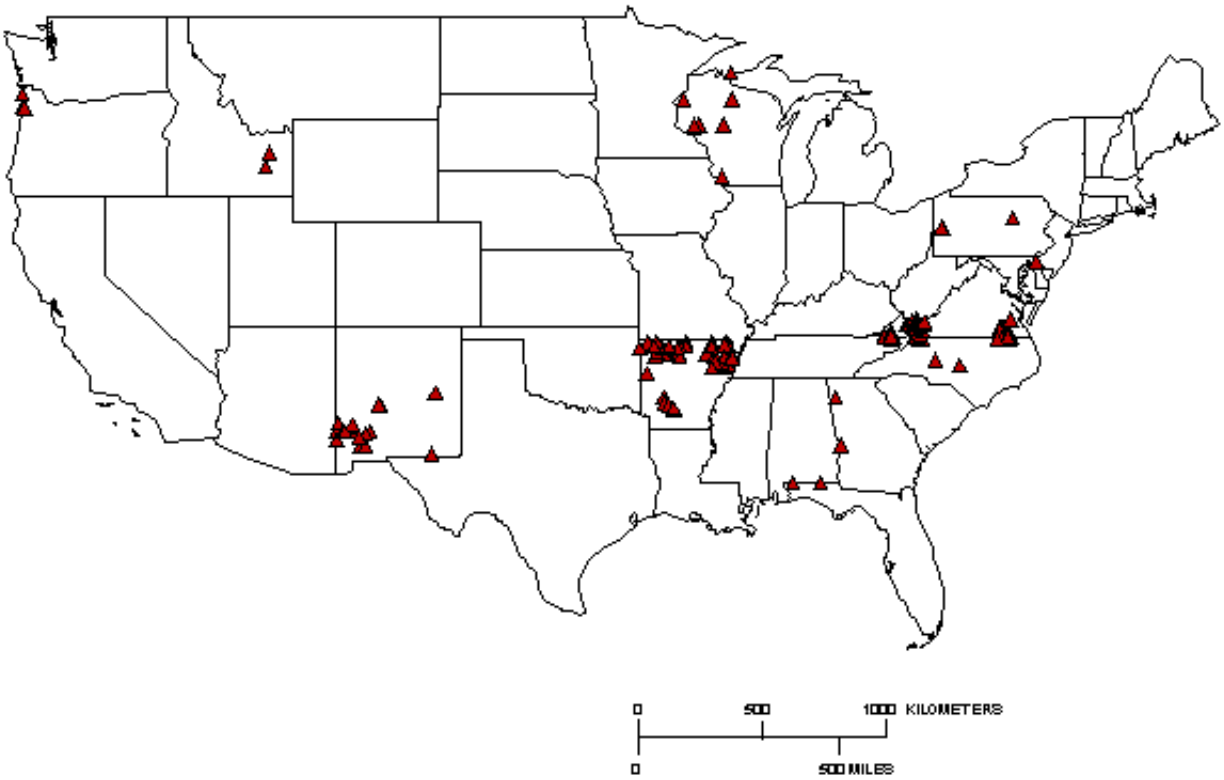

Figure 2. Generalized map of drift sites reported by States in response to request.

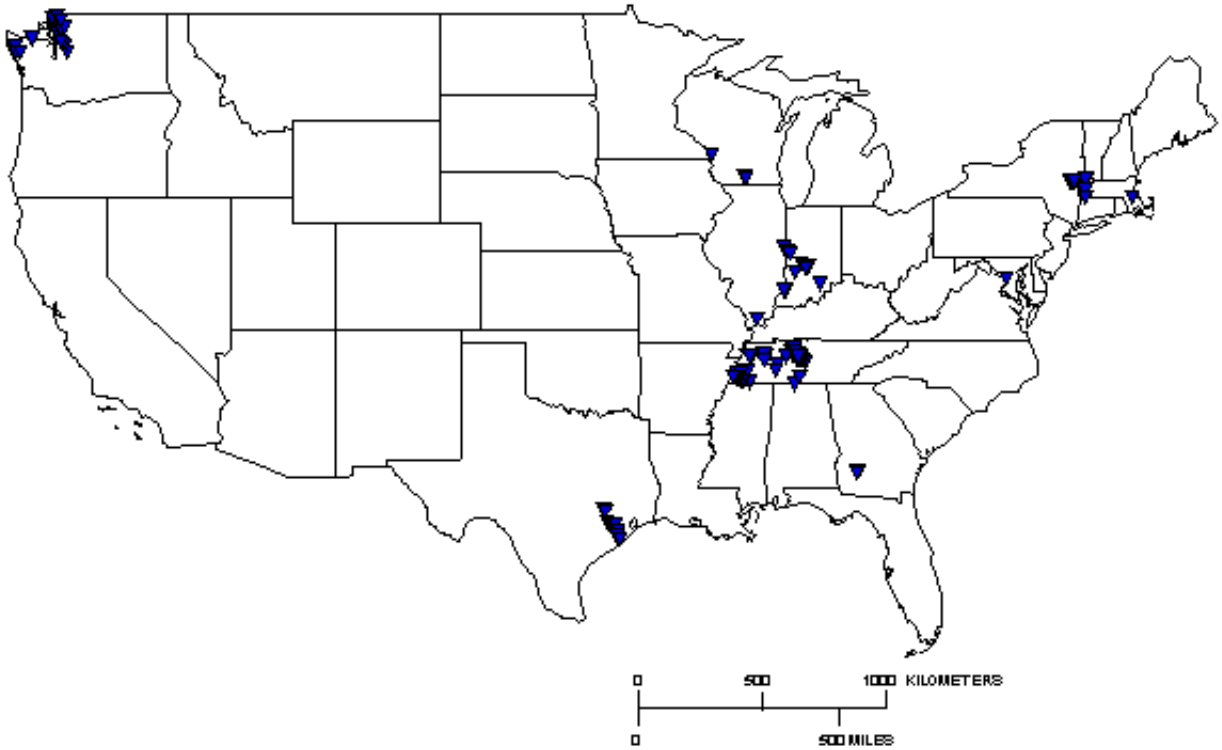

Figure 3. Generalized map of drift field-study sites.

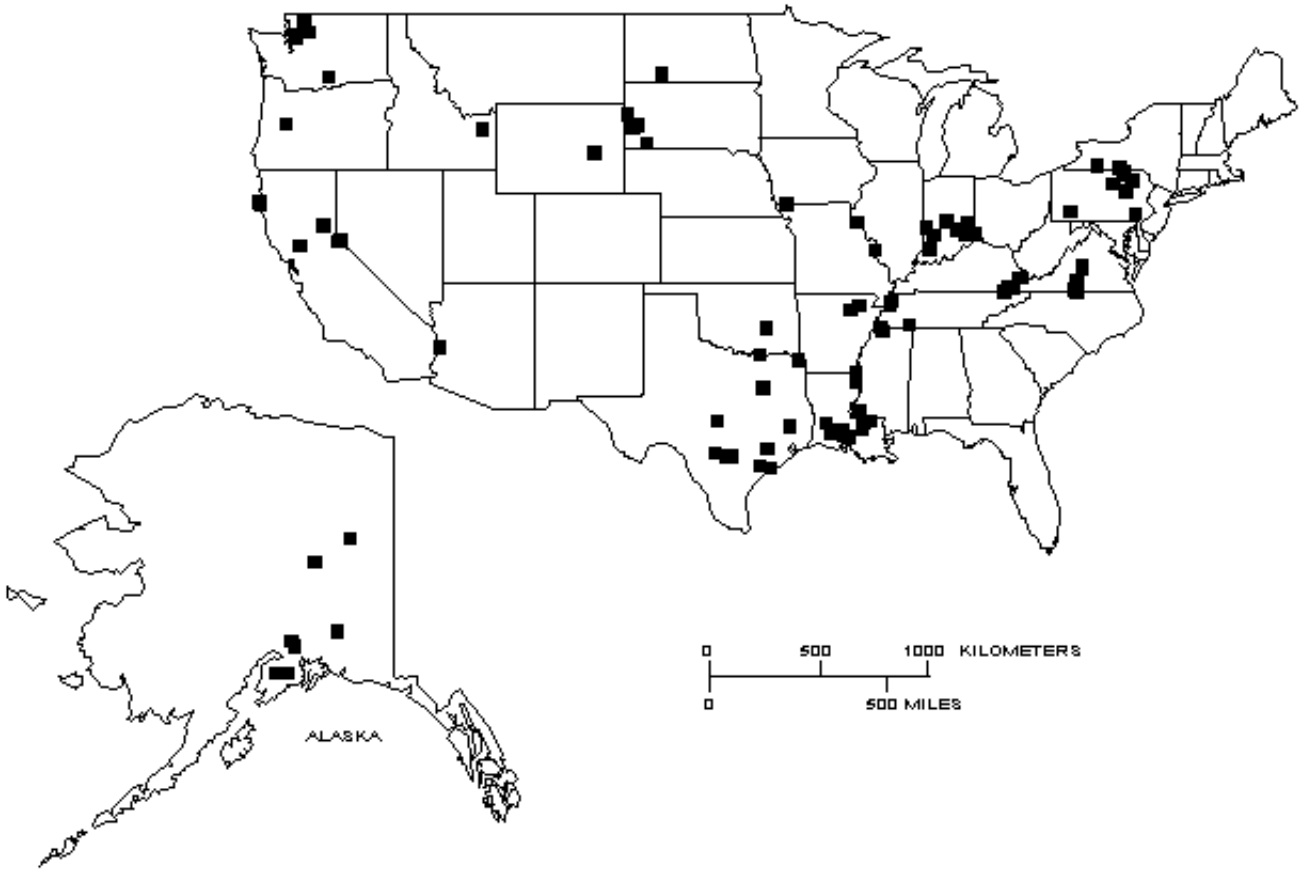

Figure 4. Generalized map of drift sites in the United States from publications and written and oral communications.

Contingency-table analysis was used to examine the association of bridge and channel characteristics with the frequency and size of drift accumulations (Mendenhall and others, 1981). Despite random variation in this data (particularly due to the random number and size of floods intervening between the inspection and the most recent removal of drift), the large number of bridges inspected justified statistical inferences.

Field studies were the major source of information on drift size, drift characteristics related to origin and transport, and the shape and structure of drift accumulations. Drift accumulations were studied at 144 drift-accumulation sites in 11 States and the District of Columbia (table 1). The typical study of a drift-laden bridge included measurement of bridge characteristics and channel dimensions, mapping of the drift accumulation in plan view, estimation of the river stage at which the accumulation occurred, and photographs of the bridge and drift. Studies performed during high flow included observations of flow characteristics and abundance and position of drift approaching the bridge. Some studies included measurements of water depth, flow velocity, and log dimensions. Sites of drift accumulation other than bridges included channels, bars, islands, and flood plains. Several sites were revisited to observe changes in accumulations, the process of drift removal, and recurrent accumulation following drift removal.

The bridges across the main stem of the Harpeth River in Middle Tennessee were visited repeatedly during the 3-year study period. Drift, bridge, and channel characteristics were analyzed to determine why particular bridges trapped most of the accumulated drift. Drift stored in the channel network of the West Harpeth River, a tributary of the Harpeth River, was inventoried to determine the volume, size distribution, and dominant sources of drift present (Diehl and Bryan, 1993).

Scanning sonar was used at the FM 2004 bridge over the Brazos River near Lake Jackson, Texas, with the cooperation of the Texas Department of Highways and Public Transportation, to measure the size and shape of a large drift accumulation. Observations of the underwater drift accumulations and the scour holes around them were made during base flow and near the peak of a major flood. The sonar was lowered from the bridge deck at two or more locations near each drift-laden pier, and scanned the area within about 24 meters (m) [80 feet (ft)]. During field work, the sonar and associated processing software were used to produce local bathymetric maps showing bridge piers, scour of the river bed, and drift. Bathymetric maps of the entire site were prepared in the office by combining the data from all scans.

SURVEY OF DEBRIS ACCUMULATIONS AT BRIDGE CROSSINGS

Data provided by H.R. Haga

VDOT

Date: 5-14-1993

1. Site Location of Debris Accumulation:
   State: VA; County Grayson; Route: 601 #6126
   Stream Crossed: New River; 0.025 miles from Rt 711

2. Bridge Description:
   Year Built: 1956; Type: Low water concrete span
   Length, total: 288 ft; Minimum span: 32 ft; Main span: 32 ft
   Clearances, from riverbed: 6 ft; from highest water mark: -- ft;
   Piers: ___ Single; ___ Double; 8 Multiple; ___ with web; X without web
   Pier alignment with flood flow: X aligned; ___ skewed __ degrees
   Channel approach to bridge: ___ straight; X curve; ___ sharp bend

3. Narrative description of debris:

   Debris consists of large & small trees, brush, bottles, cans, tires, and wood scraps. Accumulates mainly on southwest side due to current flow, sometimes entire length of bridge is blocked. Accumulates 1 to 3 times annually.

4. Characteristics of Debris:
   Type: X Logs; X Brush; X Others: Trash, bottles, jugs, tires, etc.;
   Typical length of logs: ___ less than 10 ft; ___ 10-25 ft; X over 25 ft
   Typical diameter of logs: ___ less than 1 ft; ___ 1-2 ft; X over 2 ft
   Dimensions of accumulation: length along bridge: 288 ft;
   width perpendicular to bridge: 150 ft; vertical depth: 12 ft;
   Debris lodged against: X piers; X abutments; X deck; other_____

5. Characteristics of discharge associated with debris accumulation:
   Discharge:_____ cfs;
   ___ year recurrence interval OR ___ percent duration;
   1 to 3 times annually

Figure 5. Sample State drift-accumulation report form.

6. Narrative description of damage attributed to debris:

7. Damages:

Date of occurrence: Annually 1 to 3 ;

Bridge components damaged: Superstructure, Substructure, Approaches ;

\ Degree of Damage Damage at \	Major	Some	Minor	Estimated Cost
Superstructure			X	$500.00
Substructure			X	$300.00
Approaches	X			$5000.00

8. Description of damage (attach photographs and sketches if available)

\ Effect on: Type: \	Superstructure		Substructure		Approaches	
	major	minor	major	minor	major	minor
Debris accumulation	X		X			
Debris impact	X		X		X	

9. Stream Characteristics:

Channel width 285 ft; Channel bank height 10 ft;

Dominant bed material:

clay__; silt X ; sand X ; gravel__; cobbles__; boulders X

Streambed Slope: EITHER __ percent OR __ feet per mile

Bank Material: X erodible; ___ non-erodible

Trees on bank: ___ thick; ___ some; X sparse; ___ none

Overall stability of channel: ___ unstable; ___ semi-stable; X stable

Characteristics of instability: ___ scoured banks; ___ bank failures

___ degradation; ___ aggradation; ___ lateral migration of bends

Storage: ___ reservoir upstream; ___ lake upstream; X large flood plain

Channelization; ___ throughout basin; ___ locally at bridges; ___ none

10. Basin Characteristics:

Land use: forest__%; agriculture__%; urban area__%

Lumbering operations: X active; X in the recent past; ___ none

Landslides: ___ often; X sometimes; ___ none

Wetlands: ___ extensive; X few; X mostly drained; X mostly not drained

Figure 5. Sample State drift-accumulation report form.—Continued

Previous Studies

Published accounts of drift accumulation at bridges represent only a small fraction of the cases that have occurred. Most reports do not include details such as the composition of the accumulation, its size and shape, or its position with respect to the channel and the bridge piers. Unpublished written accounts and photographs are typically not catalogued or segregated from other material in bridge files, and important details may be absent from these accounts. The memories of maintenance engineers are the largest repository of information on drift accumulation. As Brice and others (1978a) found in their study of scour problems:

> "No systematic record of bridge losses and hydraulic problems, kept separately from the files on individual bridges, was found in any state or agency; therefore, the estimates given depend on the memory and experience of the persons interviewed. Problems or losses that occurred within the last year are more likely to be recalled than those that occurred ten years ago."

Several published studies describe instances in which drift contributed to bridge failure and damage caused by scour. Brice and others (1978a, 1978b), in a study of countermeasures for hydraulic problems at 283 bridges, identified drift as contributing to scour problems at 22 bridges, and as a major cause of scour problems and bridge failures in California, Louisiana, Massachusetts, Nevada, Oklahoma, Oregon, Pennsylvania, Texas, and Wisconsin. Chang and Shen (1979) published data on drift problems at 61 bridges in the U.S. and Canada. These two studies include some of the same sites; the total number of drift-damage sites covered by the two studies is 67. Harik and others (1990) reported on 114 bridge failures in the United States, blaming one failure on drift without giving details. Smith (1976) reported on the causes of 143 bridge failures worldwide. One of these failures was caused by drift. Dongol (1989) gathered responses from local authorities in New Zealand that identified 12 bridges where drift caused failure.

Many other instances of drift accumulation have been reported in engineering literature, but few reports contain much detail about drift itself. Pangallo and others (1992) report the case of the U.S. Highway 40 bridge over the Wabash River, where a 23.6-m (77.5-ft) span was blocked, and provide photographs of six other sites of drift accumulation. Klingeman (1971) studied scour resulting from drift accumulation at the Deerhorn bridge in western Oregon. The National Transportation Safety Board (1990) reported on the failure of a temporary bridge in Ohio due to drift accumulation. Wright and Harrison (1990) reported on the details of one bridge failure due to scour and lateral loads caused by a drift raft in New Zealand. The Engineering News-Record reported a bridge failure in Tennessee caused by drift-related scour, but detailed information on the drift accumulation was unavailable (Engineering News-Record, 1980; Harik and others, 1990; James Schall, written commun., 1993). Foster (1988) reported on a modeling study of the failure of a temporary construction trestle on the Mississippi River due to scour under a drift raft. The Corps of Engineers published several photographs of bridges that failed due to drift in Hurricane Agnes (Gannett Fleming Corddry and Carpenter, Engineers, 1974).

Several unpublished accounts of drift accumulation and associated damage were provided by bridge engineers (I. Nagai, California Highway Department, written commun.., 1992; Luis Ybanez, 1992, Texas Highway Department, written commun.; James Schall, written commun., 1993; Martin Fisher, Washington State Department of Transportation, written commun., 1994; James Lukashenko, Penner and Keeler Partners, written commun., 1994; Mark Miles, Alaska Department of Transportation, oral commun., 1995). Like most published reports of drift accumulation, these accounts lack specific information on the size of drift accumulations and logs. Because information on the cross-sectional area transverse to the direction of flow is not available, indirect methods must be used to estimate drift forces and the degree of constriction of the bridge opening. The lack of information on log dimensions makes the estimation of log-impact forces more difficult.

Bridge inspection programs provide qualitative information on drift (Strautman and others, 1987; Avent and Whitmer, 1990; Huizinga and Waite, 1994; Bryan and others, 1995). Information from such programs does not include the shape, location, and porosity of drift accumulations, or the size of the component pieces. Lambeston and others (1981) recognize that drift-related forces and scour threaten bridges, and recommend inspection of the "nature and location of debris" during underwater inspections of bridges, but do not specify which drift properties should be recorded.

Potential Accumulation Size and Scour

The potential scour depth (and potential lateral forces on bridges) associated with drift depend on the maximum size that drift accumulations can reach. Methods for estimating a maximum drift-accumulation size for use in bridge design have been recommended for Australia and New Zealand, but not for the United States(American Association of State Highway and Transportation Officials, 1989).

Australian design practice assumes that the potential width of drift at a pier is equal to the average of the adjacent span lengths, up to a maximum of 20 m (66 ft), and the minimum assumed vertical depth is 1.2 m (4 ft) (National Association of Australian State Road Authorities, 1976; Wellwood and Fenwick, 1990). The potential width of drift on a submerged bridge superstructure is assumed to be the length of the superstructure. In developed river basins, the assumed minimum potential vertical depth of a drift accumulation is 1.2 m (4 ft) greater than the vertical extent of the submerged superstructure (typically, from low steel to the top of the parapet). The assumed maximum potential vertical depth is 3 m (10 ft), unless local information indicates that it should be greater (figure 6).

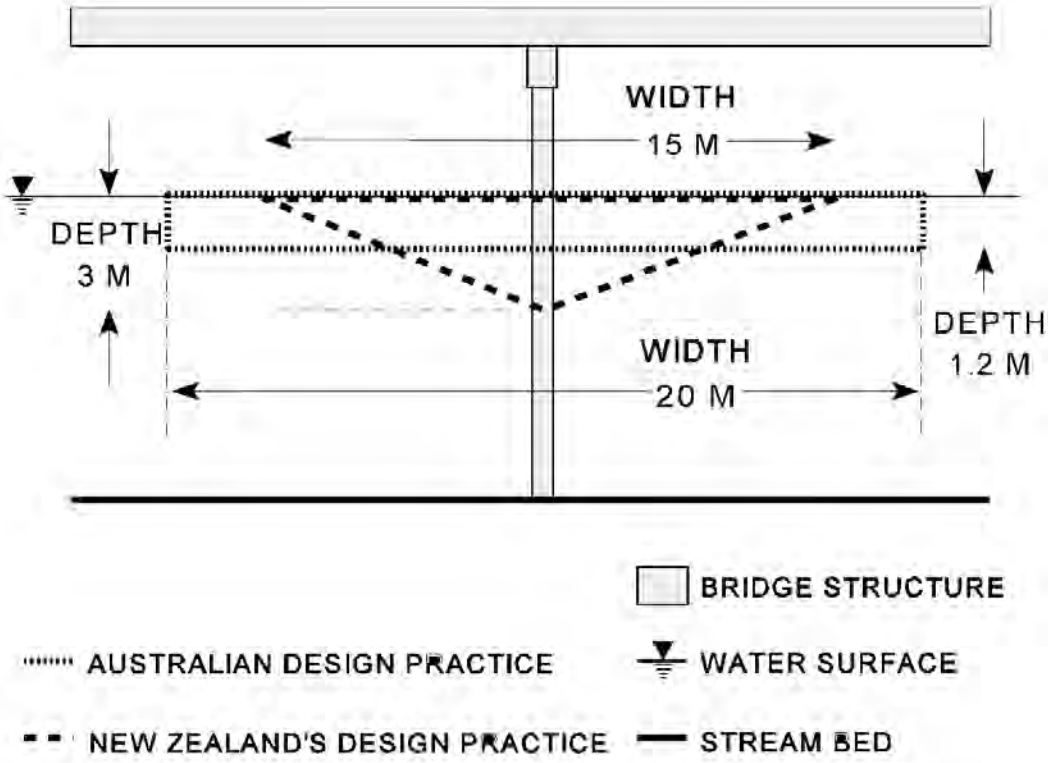

Figure 6. Vertical cross sections of assumed maximum drift accumulations on single piers.

New Zealand's design practice is similar to Australian design practice (Dr. Thomas Fenske, University of Louisville, oral commun., 1992). A draft design specification states that the potential drift accumulation at a pier can be assumed to be triangular in cross section perpendicular to the approaching flow (Dr. Arthur Parola, University of Louisville, written commun., 1992). The triangle's greatest width (at the water surface) is half the sum of the adjacent span lengths up to a maximum of 15 m (49 ft). The triangle extends vertically downward along the pier nose to a depth equal to half the total water depth or 3 m (10 ft), whichever is less (figure 6). The maximum width and depth of drift accumulations observed in this study exceed the values used in design in Australia and New Zealand.

The width of drift used in suggested Australian and New Zealand design practice may be related to the estimated length of key structural logs, and the suggested depth of drift may be based on observations of actual drift accumulations. However, no explicit basis is given for the design drift accumulations. The authors of these recommendations do not cite published or unpublished studies of actual drift accumulations, flume studies, or theoretical studies. A literature review of hydrodynamic forces on bridges, conducted at the University of Queensland in 1984, failed to uncover published accounts of the dimensions or characteristics of drift accumulations (Apelt, 1986a). As Apelt (1986b) points out:

> "The estimation of the flood loads applied to bridges by debris mats is bedevilled by lack of reliable information about the size, shape, and compactness of accumulations of debris against bridges during floods."

Scour associated with drift accumulations can be estimated based on the size of the accumulation. Pier scour depths around drift accumulations are estimated by substituting an effective pier width into a conventional pier-scour equation (Melville and Sutherland, 1988; Dongol, 1989; Melville and Dongol, 1992; Richardson and Davis, 1995). Contraction scour is calculated by reducing the area of the opening by the cross-sectional area of the drift accumulation perpendicular to the flow (Richardson and Davis, 1995). Scour underneath a drift raft can be calculated by assuming it is analogous to pressure flow under a submerged superstructure (Richardson and Davis, 1995).

Drift Countermeasures

Solid, round-nosed piers aligned to flood flow are recommended where drift is abundant (Neill, 1973; Brice and others, 1978a; Chang and Shen, 1979; Lagasse and others, 1991; Richardson and others, 1991; Richardson and Davis, 1995). Pangallo and others (1992) suggested not placing hammerhead piers in the water or pile caps above the streambed. To reduce drift accumulation, some piers have been designed with inclined upstream noses, or have been fitted with inclined drift deflectors (Brice and others, 1978a; Brice and others, 1978b; Martin, 1989).

Spaces between piles can clog with drift, increasing flow contraction and local scour depth (Brice and others, 1978a; Lagasse and others, 1991; Richardson and others, 1991; Richardson and Davis, 1995). Where pile bents or multiple-column piers are used, placement of a web wall between the columns is recommended (Brice and others, 1978a; Lagasse and others, 1991).

Long spans are less prone to drift blockage, but none of the publications that were reviewed endorsed a specific span length as adequate for North America (Bowser and Tsai, 1973; Neill, 1973; Brice and others, 1978b; Chang and Shen, 1979; Pangallo and others, 1992). In Australia and New Zealand, however, current design practices imply that spans will not be completely blocked if longer than 20 m (66 ft) or 15 m (49 ft), respectively.

Various other countermeasures have been suggested. Bridges that have adequate freeboard during the design flood are less prone to drift accumulation (Neill, 1973; Brice and others, 1978a; Chang and Shen, 1979). Several authors have recommended structures to deflect drift from piers and guide it through openings, or booms and trash racks to collect it (Kennedy, 1962; Kennedy and Lazier, 1965; McFadden and Stallion, 1976; Brice and others, 1978a; Chang and Shen, 1979; Perham, 1988; Lagasse and others, 1991; Richardson and others, 1991; Saunders and Oppenheimer, 1993). Pangallo and others (1992) suggested that piers should not be placed in the outside of bends because of the likelihood that drift will be concentrated there.

Characteristics of Drift

The predictability of many drift characteristics and processes creates opportunities for bridge engineers to improve their methods of avoiding drift problems. The processes of drift generation, transport, and accumulation interact with bridge characteristics to control the likelihood that a large accumulation will occur. The characteristics of typical pieces of drift determine the maximum size of accumulations.

Drift production and transport are natural characteristics of most rivers. The rate of drift production depends on the degree of channel instability. Channels wider than the length of logs, and deep enough that logs do not drag on the bed, transport drift efficiently. Floating trunks with attached root masses make up most of the drift volume transported to bridge sites.

The greatest amounts of drift accumulate where flow separates to pass around obstacles. Logs are the structural members of accumulations, so log characteristics determine accumulation characteristics. The length of the largest sturdy logs defines the maximum width of accumulations on single piers and the maximum length of bridge span that can be completely blocked.

Generation

Most drift is wood from trees growing close to the channel (Lyell, 1856; McFadden and Stallion, 1976; Harmon and others, 1986; Perham, 1987; Murphy and Koski, 1989; Robison and Beschta, 1990a; Lagasse and others, 1991; Diehl and Bryan, 1993). Most such trees fall into the stream as a result of bank erosion, while others are felled by wind throw, ice, disease, or old age. Flood plains can provide drift to the channel under some circumstances. Landslides and debris flows also transport large woody debris in areas of steep topography (Everitt, 1968; Keller and Swanson, 1979; Harmon and others, 1986).

Channel characteristics that determine the rate of bank erosion, such as bank height, bank angles, bank materials, erosion rates, and drift concentrations, vary from point to point within a given basin. These variations may be abrupt, and the bridge site may not represent average conditions (Diehl and Bryan, 1993). In order to assess the potential supply of drift at a bridge site, channel characteristics should be evaluated in all upstream reaches of the channel system that can transport drift, not just at the bridge site (Pangallo and others, 1992).

In the present study, most logs from bank-grown trees were recognized by curved trunks and asymmetric root masses (figure 7) (Simon and Hupp, 1992; Diehl and Bryan, 1993). Trees rooted in alluvium stabilize banks by binding sediment together with their roots. When stream banks erode, tree bases typically remain attached and project into the channel beyond the retreating bank. Growth of roots continues in the bank, while the exposed parts of the root mass become burly, develop rougher bark, and are often scarred by the impact of drift. The trunk leans toward the stream as it is deprived of support on that side, while the top of the tree grows straight upward. Logs introduced into the channel through bank erosion could sometimes be recognized by the development of strongly asymmetric root masses with fine roots only on one side. Rapid bank retreat, however, produces symmetrical logs from trees that grew on the flood plain.

Bank erosion and the resulting introduction of large woody debris are concentrated on the outside of bends where high shear stress promotes erosion (figure 8) (Elliot and Sellin, 1990; Knight and Shiono, 1990). Because the highest flow velocities are near the outside bank, trees that fall from it are likely to be mobilized and transported.

Widespread bank erosion producing abundant drift typically results from channel instability (Brice and others, 1978a; Lagasse and others, 1991). Channel instability is a natural property of some channel types, but may also result from climate change, fire, or human modifications to the channel, flood plain, or river basin. The presence of abundant drift in the channel may aggravate instability (Murgatroyd and Ternan, 1983; Gippel and others, 1992). Although channel instability may be recognized on the basis of geomorphic features and the history of the basin, the extent and rate of channel change is difficult to assess (Mueller and Dardeau, 1990). Large floods and infrequent prolonged periods of high flow may cause abrupt, extensive bank erosion even in stable channels where bank erosion is otherwise localized and slow.

A history of human alteration of the channel system and accompanying channel instability indicates that continued instability and drift production is likely. Where channelization has increased the channel slope of the main stem or major tributaries, the channel system will likely be unstable, and will continue to adjust to its new slope and alignment except where stabilization structures and non-erodible channel boundaries prevent it from doing so (Brookes, 1988; Simon and Hupp,

Figure 7. Fallen tree with asymmetric root mass and slightly curved trunk.

Figure 8. Bank erosion along outside of curve.

1992). Such adjustment may occur only in infrequent floods, producing no chronic drift problem, yet still creating high potential for abundant drift delivery during these channel-altering floods.

Extensive ditching and wetland drainage upstream from the site typically produce changes in the flow-duration relation of the stream and thus promote accelerated channel evolution. Urbanization and conversion to agriculture typically involve extensive development of ditches. Drift removal from channels can increase flow velocity, leading to channel instability and further drift production (Gippel, 1989; Gippel and others, 1992; Smith and others, 1992). Clearing of the flood plain can also promote channel instability (Brice and others, 1978a).

Logging has been cited as one of the major sources of drift (Chang and Shen, 1979; Lagasse and others, 1991). Much of the research devoted to drift and untransported large woody debris in the Pacific Northwest has been motivated by concern about timber harvesting practices that leave too much or too little large woody debris in stream channels (Ice and Lawrence, 1985; Bisson and others, 1987; Bilby and Wasserman, 1989). However, mountain and foothill streams of the Pacific Northwest historically contained large amounts of drift before logging began in the region (Orme, 1990). Drift accumulations observed in Washington contained little saw-cut material; most of the large logs in the accumulations included root masses. Of the studies reviewed, none cited forestry in gently sloping basins as a source of drift in streams.

Logging practices that directly disturb the stream corridor are responsible for most forestry-related drift (Bryant, 1980; Bryant, 1983; Bryant, 1985; Phillip D. Martin, Quinault Tribe, oral commun., 1995). Logging of the stream corridor increased the amount of woody debris in areas of steep topography with channels bounded by bedrock and gravel deposits. Current forestry practices typically include leaving a strip of trees along the stream and avoiding disturbance to the banks and bed. Where such practices are successful, logging may now be a less important source of drift than it has been in the past (Dykstra and Froelich, 1976). However, clear-cutting may increase stream discharge, leading to channel adjustment through erosion (Harr, 1976).

Wind throw of trees growing on the bank produces logs that include root masses. Erosion around wind-thrown logs may cause additional trees to be introduced into the channel (Bryant, 1980; Bryant, 1985). In basins near the Atlantic coast, hurricanes have caused the delivery of large amounts of drift, coincident with high discharge, in streams that are otherwise nearly free of drift (O'Donnell, 1973; Gannett Fleming Corddry and Carpenter, Engineers, 1974; Brice and others, 1978a).

Bank erosion, wind throw, and ice storms involve the same population of trees—those that grow on banks, bank tops, or flood plains immediately adjacent to bank tops. Wind and ice also promote the introduction of trees into the channel, but are most effective where erosion has already reduced the strength of the root system. Trees rooted in erosion-resistant materials like bedrock are much less easily detached. The prevalence of erosion over wind throw and ice damage is supported by indications of channel instability at most drift-study sites.

Flood plains may act as sources of drift where flood-plain flow is deep and few trees are present to intercept drift (Benke and Wallace, 1990; Pangallo and others, 1992). These conditions occur in the western United States along rivers where cottonwood trees grow sparsely, and in cleared flood plains where fallen or cut logs do not lie upstream of an effective barrier to

drift transport. However, deep rapid flow over flood plains did not topple or break living trees at sites observed in this study.

Some processes producing abundant drift are specific to steep, forested areas (Everitt, 1968; Calver, 1969; Swanson and Lienkaemper, 1978; Keller and Swanson, 1979; Harmon and others, 1986; Hogan, 1987; Orme, 1990). These processes include landslides, debris flows, and debris torrents; some flow events combine features of all three (Pierson and Costa, 1987). These processes occur locally and infrequently in steep slopes or channels, but may occur simultaneously at several locations in a basin in response to torrential rains. In debris torrents, drift and other debris accumulating against the upstream side of standing trees exerts sufficient force to break or uproot these trees. These trees, in turn, become part of the debris in the torrent. Debris torrents are limited to valleys with at least a 3-percent slope (Swanson and Lienkaemper, 1978; Keller and Swanson, 1979; Hogan, 1987).

Human artifacts are often included in drift accumulations. Two small accumulations appeared to be about half trash and half woody debris. Other accumulations contained objects of human origin such as lumber, fragments of buildings, toys, trash, and appliances, but these objects were not large enough, strong enough, or abundant enough to play a significant structural role.

Trees felled by beavers and humans are rarely important in drift accumulations. Beaver-cut logs were rare or absent at drift-study sites. Two reported drift accumulations in Manitoba were composed partly of drift from washed-out beaver dams (James Lukashenko, Penner and Keeler Partners, written commun., 1994). Three other reported accumulations consisted largely of sawlogs from storage areas (Brice and others, 1978b; I. Nagai, California Department of Transportation, written commun., 1992; James Lukashenko, Penner and Keeler Partners, written commun., 1994; Martin Fisher, Washington State Department of Transportation, written commun., 1995). Several accumulations contained a few saw-cut logs or lopped branches, but logging debris was never more than a small fraction of the total drift accumulation.

Drift Transport and Storage

Previous studies have shown that drift can be abundant in large floods or in prolonged periods of high water, that most drift is transported as individual logs, and that these logs tend to move along the thalweg of the stream (Chang and Shen, 1979; Lagasse and others, 1991). Effects of meanders on the orientation and location of drift have been noted (Klingeman, 1971; Pangallo and others, 1992).

Most drift floats at the water surface in a zone of surface convergence, generally where flow is deepest and fastest. As a result, floating drift is transported at about the average water velocity. Submerged drift is carried to the banks and point bars by the slower, diverging flow near the bed.

Drift in Motion

Logs are typically observed floating individually, with only temporary contact between them (figure 9) (Lagasse and others, 1991). Typical logs observed in this study lay approximately horizontal in the water, were exposed over their full length or nearly so, and did not rotate about a horizontal axis. Logs on the surface are not consistently aligned with the flow or across it, but rotate under the influence of large moving eddies.

Drift commonly aggregates into short-lived clumps. Most transported aggregations observed in this study were broken apart by turbulence, or when they struck a stationary object such as a pier or an accumulation of drift. Large drift aggregations occasionally are transported downstream (Helmericks, 1968; Rowe, 1974). In the failure of the temporary Harrison Road bridge over the Great Miami River at Miamitown, Ohio, a huge pile of drift including parts of a boat and dock struck the drift accumulation on the bridge just before failure occurred (National Transportation Safety Board, 1990).

Figure 9. Logs floating along the center of the Harpeth River at Wray Bridge, Williamson County, Tennessee.

Floating drift was typically observed in a surface-convergence zone, usually in the thread of the stream. In moderate bends, drift was observed more often along the thread between the center of the channel and the outside bank than in contact with bank vegetation. Whether floating drift followed the thread or the bank, it was typically concentrated in a path occupying only a small fraction of the channel width (figure 10).

This drift path is created by surface convergence of flow. Such convergence tends to occur at the thread of the stream. Net downward flow and divergence at the bed under the zone of surface convergence typically coincide with the thalweg. In straight rectangular or trapezoidal channels, secondary flow currents typically form a double longitudinal vortex (figure 11) (Toebes and Sooky, 1967; Chiu and Hsiung, 1981; Tominaga and others, 1989).

Bends cause the formation of a single large vortex in which the surface flow is directed toward the outside bank, and flow along the bed is directed inward and upward onto the point bar (Klingeman, 1971; Bathurst and others, 1977; Nouh and Townsend, 1979; Thorne and Hey, 1979; LaPointe and Carson, 1986; Bathurst, 1988; Johannesson and Parker, 1989). A small vortex can develop along the outside of a bend, with surface flow directing floating material away from the bank (figure 11) (Bathurst and others, 1977; Bathurst and others, 1979; Thorne and Hey, 1979; Thorne and others, 1985; Damaskinidou-Georgiadou and Smith, 1986; Bathurst, 1988).

Sunken drift is transported downstream near the bed, presumably dragging, bouncing, or tumbling along the bed. Secondary flow currents carry sunken drift to the banks in straight reaches and onto point bars in bends. As a result, sunken drift moves more slowly than floating drift and typically comes to rest away from bridges. Drift transported along the bed in deep flow is hard to observe; its abundance and importance relative to floating drift can only be inferred.

When floating drift strikes fixed objects such as piers, abutments, island heads, the streambed, or trees on the outside banks of bends, it generally continues to move downstream. Contact with fixed objects breaks the branches of floating trees, and converts them into the bare trunks with root masses common in drift accumulations. Most isolated logs on sediment bars and in pools come to rest with the root mass upstream, and the trunk and any remaining branches pointing downstream. The prevalence of this position suggests that the root mass is more likely to drag than the trunk and branches.

When a piece of drift slows relative to the flow, a visible surface wake forms around it. Such wakes were observed where floating wood struck driftwood rafts, where driftwood contacted the outside bank of bends and bank vegetation, and where driftwood removed by maintenance crews from a bridge accumulated on the river bed. Drift dragging on the bed was not observed during flood flow.

Drift can also be transported tumbling in the flow, rotating around a horizontal or inclined axis. A few tumbling pieces of drift were observed during floods.

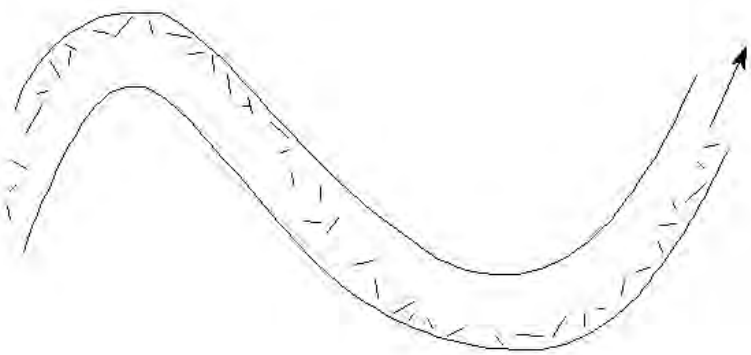

Figure 10. Generalized plan view of the path of floating drift in a meandering river.

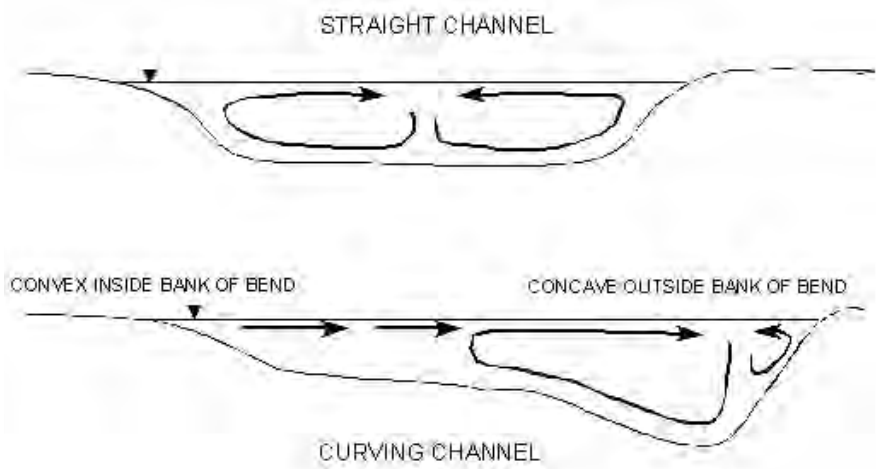

Figure 11. Patterns of secondary flow in straight and curving channels.

Stream Characteristics and Drift Storage

Transport and storage of drift depend on discharge, channel characteristics, and the size of drift pieces relative to the channel dimensions (Triska and Cromack, 1980; Bilby, 1985; Harmon and others, 1986; Bilby and Ward, 1989; Smock and others, 1989; Benke and Wallace, 1990; Robison and Beschta, 1990b). The relation of the length of typical drift pieces to the channel width is critical in determining the rate of transport and the type and amount of stored drift in the channel. The depth and slope of the channel also affect its ability to move drift. Islands, secondary channels, and flood plains influence transport and can be important sites of accumulation (Sedell and Duval, 1985).

Large woody debris in stream channels typically decays slowly. Waterlogged drift decays much more slowly than comparable drift that periodically dries out (Harmon and others, 1986; Chergui and Pattee, 1991). In the Pacific Northwest, where most of the work that addresses this topic has been done, the rate of decay of large woody debris in streams ranges from 1 percent to 3 percent per year, and much of the wood in streams is decades or even centuries old (Keller and Tally, 1979; Harmon and others, 1986; Andrus and others, 1988; Murphy and Koski, 1989; Gippel and others, 1992). Elsewhere, the rate may be higher, but even small woody debris may persist for years (Ward and Aumen, 1986; Golladay and Webster, 1988; Hauer, 1989; Chergui and Pattee, 1991). Because the dominant source of large woody debris in small channels is the infrequent fall of mature trees which then decay very slowly, streams flowing through mature forests typically contain much more large woody debris than those flowing through young second-growth forests (Sedell and others, 1988).

The narrow channels of first- and second-order streams rarely transport large drift (figure 12). Most drift is transported within the channel rather than in the flood plain. The size of drift is critical in determining whether it can be transported. Logs longer than the width of the channel typically become lodged across the channel, and rarely move without being broken into smaller pieces. In small channels with large amounts of stable woody debris, pieces with a length more than half the channel width are relatively stable. Exceptions to this pattern include steep streams subject to debris torrents, and valleys where drift is transported outside the channel over a cleared, deeply inundated flood plain.

In Bonnie Creek on Prince of Wales Island in southeast Alaska, a stream reach readily transported drift up to half the channel width in length, and the investigators determined that "...pieces with lengths about equal to bank-full width can be transported distances more than several channel widths downstream at high flow" (Lienkaemper and Swanson, 1980; Swanson and others, 1984). In streams draining old-growth timber in western Washington, Bilby and Ward reported the relation between mean length of woody-debris pieces in the channel and channel width, over a range of channel widths from 4 to 20 m (13 to 66 ft), to be:

Mean length = (0.43 * Channel width) + 3.55 m.
(Bilby and Ward, 1989)

Although trees undergo limited transport in narrow channels, these streams have been documented to transport drift (Gregory and others, 1985). Scour-potential studies recorded drift accumulations at bridges with upstream channels as narrow as 3 to 4 m (10 to 13 ft) (Noel Hurley, USGS, written commun., 1992; Ron Thompson, USGS, written commun., 1992; Bernard Helinsky, USGS, written commun., 1992; G.W. Parker, USGS, written commun., 1993). Few channels narrower than 3 m (10 ft) were included in these studies; thus, drift accumulations may be equally common in narrower channels.

In most streams of intermediate size, typically third- and fourth-order, large floods move some of the large woody debris as drift. Most drift occurs in sizable log jams containing several large pieces and typically spanning the channel (Diehl and Bryan, 1993). The abundance of drift stored in the channel typically decreases with increasing channel width, but the average size of drift pieces increases. Although the amount of drift present per kilometer of channel length in an intermediate stream is less than in a small stream, enough drift remains within the channel to form channel blockages at downstream bridges.

One consequence of the rare occurrence of drift transport in streams of intermediate width is that they typically contain a significant amount of large woody debris that has accumulated during the decades or centuries since the last major flood. The channel-wide jams that contain most of the drift may eventually be broken up and transported. Large floods can mobilize this inventory of debris and transport it downstream to bridges (O'Donnell, 1973; Gannett Fleming Corddry and Carpenter, Engineers, 1974).

Figure 12. Narrow channel bridged by fallen trees.

In low-gradient streams, the force of flowing water on stored drift is less than in high-gradient streams with the same channel dimensions. Stored drift can be abundant in large, low-gradient channels (Benke and Meyer, 1988; Benke and Wallace, 1990). Some channels have so little gradient that even floating logs are not transported any appreciable distance. The minimum slope or velocity necessary to move drift has not yet been established.

In the scour-potential studies, drift accumulations at least as wide as the bridge span were recorded in channels with bank heights as low as 0.6 m (2 ft). These studies include only a few bridges with bank heights less than 0.6 m (2 ft); therefore, that depth may not represent a minimum depth for drift transport. Drift accumulations were about as common in channels with a bank height of less than 1 m (3 ft) as in deeper channels. The width of shallow channels with extensive drift ranged from 3 m (10 ft) to 17 m (56 ft).

A shallow channel may transport only drift that is much smaller than its width would suggest. Potential for transport of large logs is low for sites along channels in which flow is never deep enough to float such logs above the bed. The depth sufficient to float a log is about the diameter of the butt plus the distance the roots extend below the butt. This is roughly 3 to 5 percent of estimated log length in the case of typical large logs observed at drift-study sites. Where large trees have fallen into shallow channels, they remain in place or move a short distance and turn parallel to the flow with their root mass upstream. However, if flow deep enough to float large logs off the bed can occur, the transport of a large inventory of logs stored in the channel is possible.

Where the depth of a wide channel is adequate to float large logs, drift may be stored on mid-channel bars and point bars, at island heads, or in pools along the base of the outside banks of bends (Wallace and Benke, 1984). Mid-channel bars may lie downstream from a zone of surface convergence so that floating drift is directed over them at high flow stages. When these bars have brush growing on them, or are only shallowly inundated, drift may form accumulations on their highest areas, promoting further sedimentation and bar growth. Stored drift in pools can easily be mobilized during a flood. Channel-wide drift accumulations are known to have occurred in wide channels, but such accumulations are presently rare (Young, 1837; Triska, 1984).

Islands may intercept drift, forming island-head jams or accumulations on trees growing on the island crest. Island-head accumulations grow in the upstream direction through accretion of additional drift and promote island growth in the downstream direction through sedimentation (Crockett, 1955; Helmericks, 1968; Gippel and others, 1992).

In most wide streams, typically fifth-order and larger, not much drift is stored within the channel, and nearly all drift entering the main channel is transported by frequent floods. Most drift accumulates outside the channel on islands, on forested bars, in flood-plain forests, and in sloughs (McFadden and Stallion, 1976; Sedell and Duval, 1985; Malanson and Butler, 1990; Chergui and Pattee, 1991). Observations of stored drift in or near large channels confirm that the channel has the potential to deliver abundant drift to a highway crossing downstream.

Flow patterns change as a river floods. As stage rises, more islands and chutes (secondary channels) are present. At the downstream end of bends, surface flow emerging from the zone of surface convergence in the bend may direct concentrated drift across an inundated point bar rather than across the channel to the outside of the next bend. Bridge piers on cleared point bars and flood plains have potential to collect drift (Klingeman, 1971; I. Nagai, California Department of Transportation, written commun., 1992). When inundated, forested point bars may collect large accumulations of drift, especially where the pattern of flood flow directs the drift path into the woods.

Chutes may receive most of the drift in the river if they begin on the outside of a bend, especially toward the lower end of the bend (Damaskinidou-Georgiadou and Smith, 1986). Chutes too narrow or too shallow to transport the drift they receive become sites for accumulation (McFadden and Stallion, 1976). An accumulation on the head of the island separating the secondary and main channels may grow upstream and block the chute entrance.

When the depth of flood-plain inundation exceeds roughly one-third the channel depth, the zone of surface convergence in the channel becomes discontinuous or ceases to exist, and most surface flow follows the axis of the valley (Toebes and Sooky, 1967; Elliot and Sellin, 1990; Knight and Shiono, 1990). The distance between trees in a typical flood-plain forest is much less than the length of an average log, so the forest acts as a trash rack (Kochel and others, 1987). Accumulations on the upstream sides of flood-plain trees were observed at several sites during this study. Except where trees are sparse, flood plains remove more drift from the river than they add (Benke and Wallace, 1990).

Management of Drift

Management of drift in the channel has typically focused on drift removal, bank clearing, and channel modifications. Removal of accumulated drift at bridges and in upstream channels is common (Brice and others, 1978a; Lagasse and others, 1991). At some sites, trash racks intercept and collect transported drift. The complex problems of stabilizing channels to reduce drift generation have been addressed in few locations (Gippel, 1989; Gippel and others, 1992).

Many wide streams in the United States were impeded by large drift accumulations at the time of European settlement (Young, 1837; Sedell and Frogatt, 1984; Triska, 1984; Wallace and Benke, 1984; Harmon and others, 1986; Sedell and others, 1988; Orme, 1990). Drift was abundant in streams of all sizes. Beaver created drift by felling trees and creating ponds that killed trees, but their dams probably stabilized more drift than they mobilized (Naiman and others, 1986).

The relatively unimpeded channels now present are the product of intensive ongoing drift removal (Nunnally and Keller, 1979; Shields and Nunnally, 1984). Beginning shortly after European settlement, drift jams were removed to allow navigation and promote drainage. Logging of virgin timber was accompanied by efforts to increase the capacity of channels to transport logs (Sedell and Duval, 1985; Perham, 1988). Clearing and snagging of channels has been a common practice from the time of settlement to the present (1996).

Drift removal has mixed effects on flood conveyance (Gippel and others, 1992; Smith and Shields, 1990; Young, 1991; Shields and Gippel, 1995). A detailed study of partial drift removal in the South Fork Obion River, Tennessee, reported that "...flood control benefits of LWD [large woody debris] removal may be extremely limited in channels similar to the one studied." (Smith and others, 1992). Not all claims of greater flow velocity after drift removal are justified. When increased velocity does result, the flood wave may move downstream faster and increase flood stages downstream from the cleared reach. In large rivers, the effect of drift removal on bank-full conveyance may be negligible. The practice of clearing and snagging, which combines drift removal and bank clearing, is typically intended to increase conveyance, but may cause channel instability and produce a wider and shallower channel with lower conveyance (Thorne, 1990).

Channel modifications to prevent drift accumulation include channel straightening, channel enlargement, drift removal, and the elimination of islands, sloughs, and side channels. These modifications, which resemble those historically used to enable water transportation of logs, are generally successful in promoting drift transport (Sedell and Duval, 1985). Where channel modifications cause channel widening, the abundant drift generated is delivered downstream (Diehl, 1994).

Drift removal, once considered beneficial to fish, is now regarded as detrimental to stream ecology (Gippel, 1989; Gippel and others, 1992). Large woody debris provides a substrate for aquatic invertebrates, stores sediment, and through its effects on channel morphology creates invertebrate and fish habitat (Zimmerman and others, 1967; Megahan, 1982; Wallace and Benke, 1984; Benke and others, 1985; Heede, 1985; Shine, 1985; Bisson and others, 1987; Klein and others, 1987; MacDonald and Keller, 1987; Cherry and Beschta, 1989; Smock and others, 1989; Benke and Wallace, 1990; Carlson and others, 1990; Sedell and others, 1990). Woody debris in road ditches has effects similar to those in low-order channels, trapping sediment and providing invertebrate habitat (Duncan and others, 1987; Hammer, 1989).

New forms of channel management are designed to remove as little drift as possible while still achieving management goals. Forest is allowed to remain in the stream corridor to provide a source of large woody debris sufficient to sustain a large debris inventory in the stream over the long term (Froehlich, 1973; Dykstra and Froehlich, 1976; Bisson and others, 1987; Bilby and Wasserman, 1989). In some areas of the United States, managers have begun to place large woody debris in streams from which it was formerly removed (Gippel and others, 1992). As a result of such changes in management, logs from large mature trees may become more abundant in rivers in the next 50 to 200 years (Bilby and Likens, 1980; Likens and Bilby, 1982; Hogan, 1987; Andrus and others, 1988; Hauer, 1989; Gippel and others, 1992).

Trash racks and holding booms are well-known devices for collecting drift (Perham, 1987; Perham, 1988). Trash racks can collect all the large drift transported in the channel (figure 13). Flow transporting drift distributes it to unblocked portions of the rack, which then become clogged. Booms seem most effective where currents are slow, but net booms are effective even in faster flow.

The most serious problem in using trash racks or holding booms to protect highway bridges from drift delivery is the large amount of drift that can be transported through the relatively small channel cross section. In one study, the estimated amount of floating debris transported from a 260-square-kilometer (100-square-mile) basin in the design flood was 54,000 cubic meters (1,925,000 cubic feet) (Martin, 1989). This is much more than enough to completely block the channel. Site studies conducted as part of this project and scour-potential studies include observations of many drift accumulations that formed on bridges with a much lower trapping efficiency than a trash rack, yet blocked most of the channel (figure 14). The existence of such accumulations indicates that a single flood in some rivers may transport more than enough drift to block the channel completely.

If the trash rack clogs completely, blockage of the channel will produce significant backwater upstream. Unless the trash rack is designed to function as a dam, scour may be severe downstream from the rack or where flow re-enters the channel. If the trash rack is just upstream from the bridge, it could increase contraction and local scour.

A second, related problem is the cost of drift removal. A trash rack collects much more drift than a bridge at the same location would trap. This drift must be removed to maintain the function of the rack, so the cost of removal should be considered as part of the cost of the trash rack. The chance of drift remaining in place until the next flood is higher where removal is difficult.

Figure 13. Trash rack and accumulated drift in Georges Creek near New Columbia, Illinois.

Figure 14. Nearly complete channel blockage of the Harpeth River at Interstate 40, Davidson County, Tennessee.

Accumulation at Bridges

Drift accumulates at bridges when it encounters structural components that trap it. Most observed drift accumulations fall into two classes: single-pier accumulations and span blockages. Consistent features of observed accumulations allow prediction of probable locations and maximum size of potential accumulations.

A probable maximum width of drift accumulations and blocked spans can be estimated on the basis of known drift characteristics or, lacking detailed information on drift, on the basis of channel width upstream from the site. Wider span blockages and single-pier accumulations are rare, and seem to involve the formation of mid-channel bars through massive sedimentation or the accumulation of exceptionally large drift.

No limit to the vertical extent of accumulations has been established other than the depth of flow. In the process of formation, single-pier accumulations often take on a form roughly resembling the inverted half-cone shape implied by New Zealand's design criteria (Dongol, 1989; Dr. Arthur Parola, University of Louisville, written commun., 1992). Under some circumstances, drift accumulations can reach from the water surface to the river bed. The maximum vertical extent of drift accumulation observed in this study was more than 12 m (40 ft).

Unlike drift delivery, which is commonly beyond the control of bridge engineers, drift trapping can be reduced by appropriate design features such as adequate freeboard, long spans, solid piers, and careful pier placement. Measures designed to guide drift through existing structures have had mixed results.

Width of Accumulations and Blocked Spans

The length of the longest pieces of drift determines the maximum width of the common types of drift accumulation. Long logs hold together large accumulations and support them against lateral forces. The width of the channel influences the length of drift delivered to the bridge, and thereby helps to determine accumulation potential and characteristics.

Width of Observed Single-Pier Accumulations

An accumulation resting against a single pier typically contains one or more logs extending the full width of the accumulation perpendicular to the approaching flow. These key structural logs convey lateral hydraulic forces to the pier and prevent the accumulation from breaking apart and passing downstream on both sides of the pier. Sometimes these logs are visible (figure 15). Single-pier accumulations without

Figure 15. Large log supporting a single-pier drift accumulation.

visible full-width logs generally contain smaller logs arranged in a pattern similar to the smaller logs in accumulations with visible, full-width logs. This common pattern suggests that full-width logs are present, but either submerged or concealed beneath smaller drift.

The upstream ends of some large accumulations that form across spans and on island heads have the same structural pattern as single-pier accumulations (figure 16). Island-head accumulations typically terminate in a raft one log thick at its upstream edge, with individual logs extending its full width. The raft typically has a curved upstream edge when viewed from above, and the center of its downstream side rests across thicker parts of the accumulation that support the raft against lateral hydraulic forces.

The submerged drift accumulation surveyed with scanning sonar at the FM 2004 bridge over the Brazos River near Lake Jackson, Texas, was about 23 m (about 75 feet) wide, or about as wide as the length of the largest logs in the Brazos River. It had an irregular, convex upstream face. The floating raft of drift that formed over this accumulation during a flood had about the same width and length, and a curved upstream edge (figure 17).

Data from scour-potential studies are consistent with the structural pattern observed in single-pier accumulations. Plots of drift width versus upstream channel width (for drift accumulations presumed not to span the gap between two piers) show that few accumulations on a single pier are more than 15 m (50 ft) wide (figures 18 and 19). In narrow channels, such accumulations tend to be narrower than the channel.

Single-pier and island-head accumulations wider than the length of a single log were observed at three sites along the White River of Indiana. The White River has a wide-bend point-bar channel with a high rate of lateral migration (Brice and others, 1978a). All of these unusually wide accumulations were at sites with potential for bar aggradation and island development. At Paragon, Indiana, island growth clearly contributed to the large size of the accumulation. The island and the upstream part of the accumulation formed part of a scroll bar, one of the longitudinal sand bars that characteristically form parallel to the inside bank of channel bends.

Figure 16. Drift accumulation at the upstream end of an island.

Figure 17. Raft of floating drift at the FM 2004 bridge over the Brazos River near Lake Jackson, Texas.

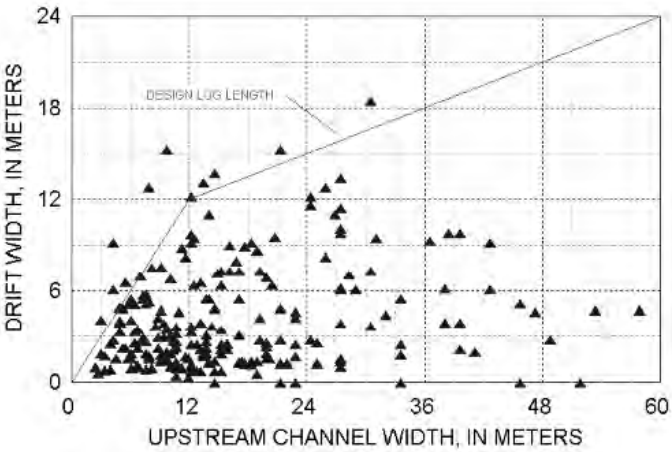

Figure 18. Width of inferred single-pier drift accumulations at scour-potential sites in Indiana.

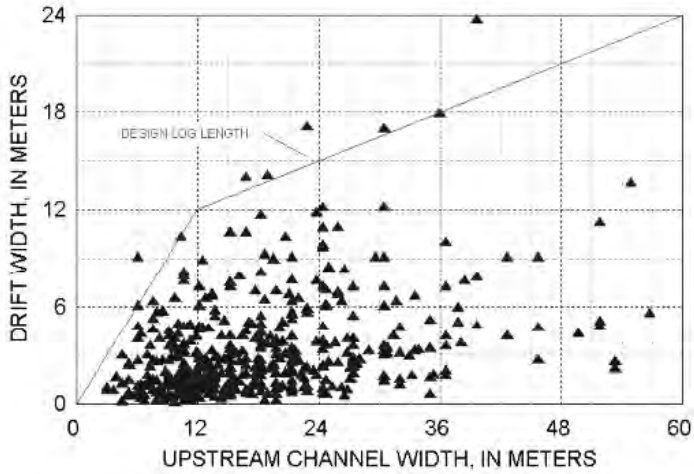

Figure 19. Width of inferred single-pier drift accumulations at scour-potential sites in Tennessee.

Width of Observed Span Blockages

Drift accumulations between piers typically occur where the length of drifting logs exceeds the effective width of openings between piers, and the logs can come to rest against two piers (figure 20). The effective width between piers is the distance between lines parallel to the approaching flow that pass through the nose of each pier (figure 21). Any fixed object that divides the flow can provide a place for one end of a log to rest. Such objects include island heads, trees and utility poles on the flood plain, and isolated piers and pilings remaining from previous bridges at the same site.

Where the structure of logs bridging the gap between piers could be observed, individual logs typically bridged the gap between piers. Some of these key logs rested directly on the piers; others rested against drift accumulated on the pier noses. In all confirmed cases of drift extending from pier to pier without interaction with additional stationary objects, the effective span was short enough to be bridged by a single log (figure 22).

At most sites with narrow channels, the main span must bridge the entire channel to achieve low potential for span blockage. Many box culverts and timber trestles have an effective span length much shorter than the channel width upstream or the typical length of the longest drift in the stream. At such sites, span blockage is the dominant mode for large drift accumulations, and considerations of pier placement and single-pier accumulations are of secondary importance.

Study of bridges along the Harpeth and Wolf Rivers in Tennessee confirmed the importance of span length in determining which bridges underwent span blockage. On the Harpeth River, bridges with spans shorter than the length of large logs (15 to 18 m, or about 50 to 60 ft) typically had one or more spans blocked at least once, whereas longer spans were not blocked. Most of the oldest and newest bridges along the Harpeth River have long spans. Current design practice seems to favor spans in the range of 20 to 30 m (about 70 to 100 ft) and single-column piers with rounded noses. Such bridges did not undergo span blockage during the study period. Most bridges along the lower Wolf River have spans longer than 18 m (60 ft). No blocked spans were observed on these bridges. During a period of high water on the Wolf River, abundant drift formed several single-pier accumulations, but did not bridge any spans.

Figure 20. Logs lodged from pier to pier and from pier to bank.

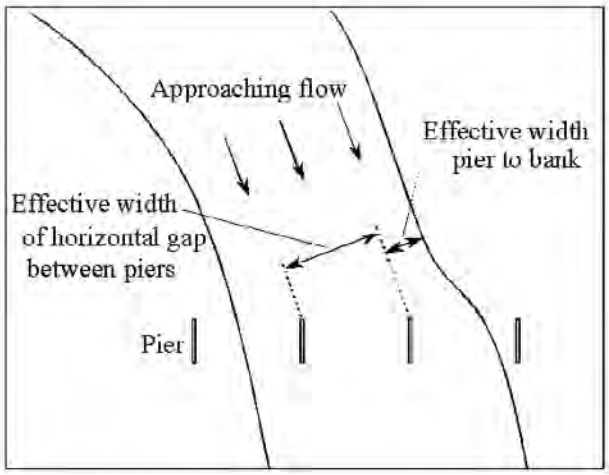

Figure 21. Definition sketch of the effective width of horizontal gaps.

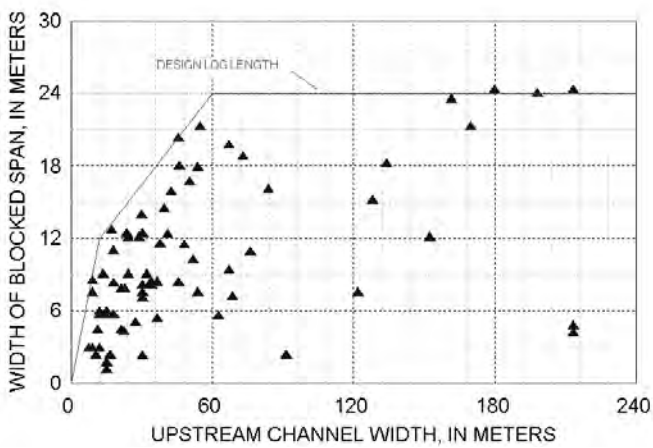

Figure 22. Effective width of drift-blocked spans outside the Pacific Northwest.

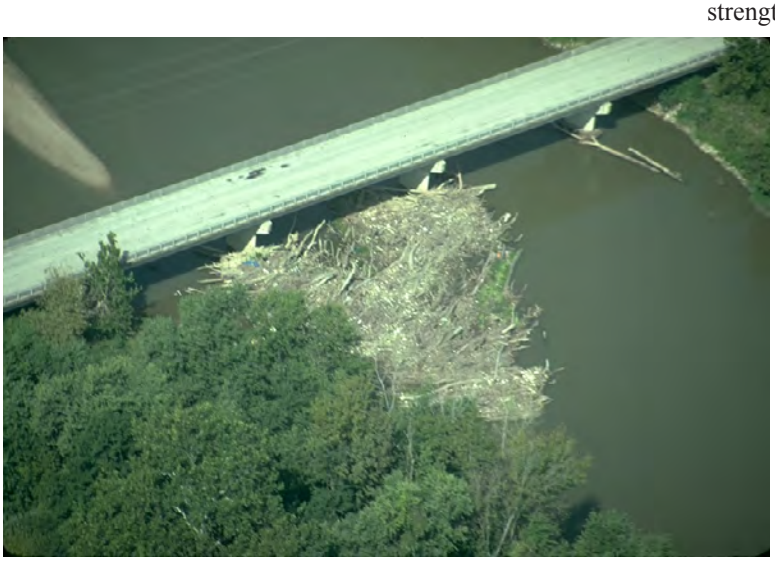

Figure 23. Blockage of a 27-meter span over the White River at Paragon, Indiana, by drift accumulation and island formation, September 25, 1992.

Wide spans can be bridged by drift accumulations where the size of the drift exceeds the effective span width. An extreme example is the accumulation that occurred in June, 1994, in the Brazos River at U.S. Highway 59, near Richmond, Texas (David Dunn, USGS, oral commun., 1994; James Fisher, USGS, oral commun., 1994; David Mueller, USGS, oral commun., 1995). At that location, flow approached two parallel bridges at an angle of about 45 degrees to the highway centerline. This situation produced an effective span length of about 24 to 27 m (70 to 80 ft), although the span length along the centerline of the bridges is 56 m (185 ft). A large accumulation grew directly upstream from a pier on the downstream bridge into the middle of a span of the upstream bridge. Additional drift accumulated between the head of this accumulation and the adjacent piers of the upstream bridge. In Steamboat Slough at Interstate 5 near Everett, Washington, 37-m (120-ft) spans were blocked (Brice and others, 1978b; Martin Fisher, Washington DOT, written commun., 1994). Sawlogs that were cabled together into rafts wider than the spans broke free from a storage area and became lodged against the spans. On the White River near Paragon, Indiana, the blockage of a 27-m (90-ft) span was related to the growth of an island upstream from the span (figure 23).

On the Harpeth River at Tennessee State Route 250 near Frog Pond, Tennessee, a span was bridged by drift extending from a single-pier accumulation to the side of a span blockage. This drift was washed away in a subsequent period of high water, leaving the single-pier accumulation and span blockage intact. This was the only observed instance in which the narrow gap between adjacent drift accumulations trapped drift in a manner analogous to a gap between piers. Such a structural pattern would seem to require the development of significant shear strength between the logs in the mass of drift. A theoretical basis exists for the development of shear strength capable of supporting lateral forces over a greater width perpendicular to flow than the length of single logs (Kennedy, 1962). However, wide span blockages that involve the development of shear strength in an accumulation of drift seem to be rare.

Where several adjacent spans are short enough to be bridged by drift, the accumulation can extend across all spans to which drift is delivered, sometimes blocking nearly all of the channel and producing significant backwater. On the Harpeth River at State Route 46, for example, two of the 14-m (46-ft) spans and most of the third span were blocked, causing about 1 m (3 ft) of backwater and supercritical flow through the remaining chute. Drift can also accumulate on immersed superstructures, and can extend across all areas to which drift is delivered.

Accumulations between a pier and an abutment or bank are similar in structure to accumulations between piers. Large, sturdy, fixed objects on the bank, such as boulders and trees, can support one end of a log. Logs can become lodged perpendicular to flow against a pier and a tree or boulder just as they would across two piers. Woody vegetation and riprap on river banks at bridges may make such accumulations possible at most

sites. Based on this possibility, the effective width between a pier and a bank or abutment is the distance perpendicular to the approaching flow between a line projected upstream from the pier nose and the nearest point on the bank or abutment (figure 21).

More typically, such accumulations extend diagonally upstream from the pier to the bank. Banks without objects projecting into the flow apparently trap one end of a log only when it is forced into the bank. At the other end of the log, a corresponding force away from the bank is exerted on the pier. Logs trapped diagonally must be somewhat longer than the effective span. Measures that keep the bank smooth (such as clearing the right-of-way of woody vegetation) may reduce the potential for drift to accumulate between the banks and nearby piers (figure 20).

Design Log Length

Site studies show that log length is the most important factor influencing accumulation width. Site studies and the descriptive statistics of larger sets of drift-laden bridges also show that drift-accumulation width on single piers and the width of blocked spans are related to upstream channel width. (figures 18, 19, and 21). In this report, a design log length for use in estimating the potential for drift accumulation is inferred from the width of the largest single-pier accumulations and the longest blocked spans.

Because single-pier drift accumulations are based on logs extending the full width of the accumulation, and spans are blocked by logs extending from pier to pier, the maximum width of these types of accumulation is about equal to the maximum length of sturdy logs delivered to bridges. This design log length does not represent the absolute maximum length of drift pieces; longer pieces were observed at several sites. It represents a length above which logs are insufficiently abundant, or insufficiently strong throughout their full length, to produce drift accumulations equal to their length.

Design log length is defined at a given site by the smallest of three values:

- the width of the channel upstream from the site,
- the maximum length of sturdy logs, and
- in much of the United States, 9 m (30 ft) plus one quarter of the width of the channel upstream from the site.

The minimum width of relatively narrow channel reaches immediately upstream from the bridge can be used as an estimate of the length of the longest logs arriving at the bridge (Lagasse and others, 1991). Channels less than 12 m (40 ft) wide with forested banks receive an abundant influx of logs longer than one channel width when generation processes are active. Drift transported over a long distance is limited to pieces too short to jam between banks or between trees on opposite banks. Longer drift either accumulates or is broken until it can fit crosswise in the channel. As a result, few logs arriving at a bridge are able to span the distance between piers farther apart than the width of the channel upstream from the bridge.

The height and diameter of mature trees on the banks determine the maximum length of the logs that are delivered to the bridge as drift and are capable of withstanding hydraulic forces when forced against piers. This maximum sturdy-log length seems to reach about 24 m (about 80 ft) in much of the eastern United States, and may be as long as about 45 m (about 150 ft) in parts of northern California and the Pacific Northwest.

Typical mature heights of tree species common on river banks are not identical to maximum sturdy-log length, but give a rough guide to the maximum length of transported logs that can be expected in wide rivers. A comparison of mature tree heights among forest regions can be used to illustrate possible regional differences in the design log length and corresponding differences in maximum widths of accumulation and span blockage (table 2). The maximum sturdy-log length can be modified to fit regional and local conditions as more data on actual dimensions of transported logs are gathered.

Throughout much of the United States, the maximum sturdy-log length is 24 m (80 ft). In the Southern Forest Region and Central Forest Region, several tree species common on moist sites reach mature heights between 24 and 30 m (80 and 100 ft) (Preston, 1976). These species provide the large logs in accumulations observed in Indiana, Georgia, Tennessee, and Texas, and those that have occurred in most of the Eastern United States. On the Great Plains, some typical eastern species of large hardwoods extend westward along river valleys to the limits of their ranges. Probably the most extensively distributed large tree along rivers of the Great Plains is the cottonwood. The cottonwood can produce large logs, as shown by the blockage of multiple 24-m (80-ft) spans by cottonwood logs in Idaho.

In those parts of the United States where the maximum sturdy-log length is 24 m (80 ft), design log length is less than either the upstream channel width or the maximum sturdy-log length over an intermediate range of channel width from 12 m to 60 m (40 to 200 ft). Based on the width of drift accumulations and blocked spans, the design log length over this range of channel width is 9 m (30 ft) plus one quarter of the channel width (figure 24). This third constraint on design log length reflects the rarity of long logs and their breakage during transport.

Local knowledge should be used to select a regional maximum sturdy-log length in Washington, Oregon, coastal Alaska, and northwestern California. Many trees of the Pacific Coast Forest Region are more than 30 m (100 ft) high at maturity. Sturdy logs from 30 m (100 ft) to 45 m (150 ft) long were observed in Washington, and sturdy logs more than 24 m (80 ft) long are common. Single-pier accumulations as wide as about 50 m (about 170 ft), and blocked spans as wide as about 45 m (about 150 ft) were observed in this study (figure 25). Other comparable accumulations have been reported (I. Nagai, California Department of Transportation, written commun., 1992; Phillip D. Martin, Quinault Tribe, oral commun., 1995).

Table 2. Height and diameter of mature large trees, by region and species.

[--, no data in Preston, 1976]

Tree heights based on North American Trees by Preston (1976)				
Forest Region	Height range, in meters		Diameter range, in meters	
	Minimum	Maximum	Minimum	Maximum
Southern Forest Region				
Baldcypress	30	37	0.9	1.5
Sweetgum	24	37	0.6	1.2
White Oak	24	30	0.9	1.2
Shumard Oak	24	30	0.9	1.5
Willow Oak	21	30	0.6	1.2
Loblolly Pine	27	34	0.6	0.9
Slash Pine	24	30	0.6	0.9
Central Hardwood Forest Region				
White Oak	24	30	0.9	1.2
American Elm	23	30	0.9	1.8
Sweetgum	24	37	0.6	1.2
YellowPoplar	24	30	1.2	1.8
Northern Forest Region				
White Pine	27	55	0.0	0.8
Red Pine	18	24	0.6	0.9
Red Spruce	21	24	0.5	0.6
Yellow Birch	18	24	0.3	0.6
Beech	18	24	0.6	0.9
Basswood	18	24	0.6	0.9
Sugar Maple	18	24	0.6	0.9
Black Maple	18	24	0.6	0.9
Red Maple	18	24	0.6	0.9
Silver Maple	18	24	0.6	0.9
Northern Red Oak	18	24	0.6	1.2
Balsam Poplar	18	24	0.3	0.9

Tree heights based on North American Trees by Preston (1976)				
Forest Region	Height range, in meters		Diameter range, in meters	
	Minimum	Maximum	Minimum	Maximum
Rocky Mountain Forest Region				
Engelman Spruce	18	37	0.5	0.9
Subalpine Fir	18	30	0.5	0.6
Western White Pine	27	55	--	0.8
Lodgepole Pine	21	24	0.4	0.8
Balsam Poplar	18	24	0.3	0.9
Ponderosa Pine	46	55	0.9	1.2
Western Larch	43	55	0.9	1.2
Douglas Fir	--	40	--	--
Narrowleaf Cottonwood	15	21	0.3	0.5
Peachleaf Willow	18	21	--	0.6
Broadleafed Cottonwoods	18	30	0.9	1.5
Pacific Coast Forest Region				
Coast Redwood	61	84	2.4	3.7
Douglas Fir	--	91	--	--
Ponderosa Pine	46	55	0.9	1.2
Sugar Pine	53	61	0.9	1.5
Jeffrey Pine	30	55	1.2	1.8
Western Hemlock	38	53	0.6	1.2
White Fir	37	46	0.9	1.2
Grand Fir	43	49	0.6	1.2
Pacific Silver Fir	43	49	0.6	1.2
California Red Fir	46	55	1.2	1.5
Noble Fir	46	61	1.2	1.8
Western Red Cedar	46	61	1.2	2.4
Sitka Spruce	55	61	0.9	1.4
Port Orford Cypress	43	55	1.2	1.8
Black Cottonwood	--	61	--	2.4
Red Alder	24	30	0.3	0.9
Bigleaf Maple	24	30	0.9	1.2
California White Oak	18	24	0.9	1.5

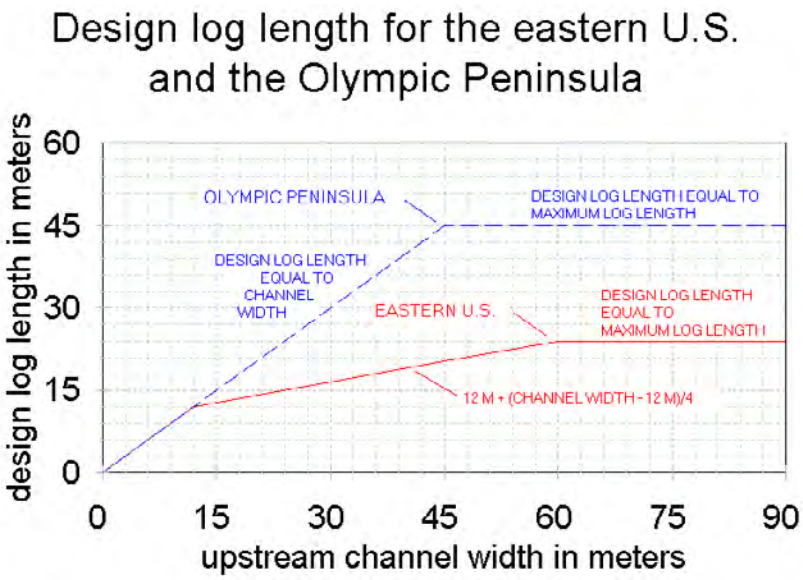

Figure 24. Design log length and upstream channel width for the eastern United States and the Olympic Peninsula.

Figure 25. Widest observed single-pier accumulation, in the Queets River, Washington, at Clearwater River Road.

Where many logs exceed 24 m (80 ft), design log length is equal to the lesser of either upstream channel width or the regional maximum sturdy-log length (figure 24). In the Pacific Northwest, there seems to be no intermediate range of channel width over which design log length is less than both channel width and the maximum sturdy-log length.

The Alaskan interior may have a maximum sturdy-log length comparable to that in the Eastern United States. McFadden and Stallion (1976) measured the length of spruce, birch, cottonwood, larch, and aspen logs in the Chena River in central Alaska. The average log was 12 m (39 ft) long, two-thirds of the logs were between 7 and 16 m (24 and 54 ft) long, and the longest log was 26 m (85 ft) long.

Across the northern tier of the eastern United States, only a few species reach mature heights of more than 24 m (80ft). The largest common species in this size class are white oak, yellow poplar, cottonwood, white pine, and American elm. The first three of these species are rare or absent in a region stretching along the Canadian border across northern Minnesota, Wisconsin, Michigan, and New York, and across most of Vermont, New Hampshire, and Maine. Large white pines are rare, and American elm is increasingly rare due to the spread of Dutch elm disease. Thus, along the Canadian border, trees reaching typical mature heights greater than 24 m (80 ft) are relatively rare. The maximum sturdy-log length and corresponding drift-accumulation width in this region may be less than in areas farther south. Data presently available on the dimensions of transported logs and the maximum width of drift accumulations are insufficient to define this shorter maximum sturdy-log length precisely; based on two examples of blocked spans in Manitoba, it is at least 18 m (60 ft) (James Lukashenko, Penner and Keeler Partners, written commun., 1994).

If drift removal and streambank clearing cease, the maximum sturdy-log length will likely increase. Before extensive snag removal (mostly from 1870 to 1920), logs in North American rivers were much larger (Sedell and Frogatt, 1984; Triska, 1984; Sedell and others, 1988). The largest logs in the Red River (Louisiana) jam were 30 to 36 m (100 to 120 ft) long and as much as 1.75 m (6 ft) in diameter. Snags, primarily sycamore and cottonwood, were historically abundant in

the lower Mississippi River. On the average, these logs were 1.7 m (6 ft) in diameter at the base, 0.7 m (2 ft) in diameter at the top, and 35 m (115 ft) long. On the Williamette River of Oregon, the very abundant snags were, on the average, 0.5 to 2 m (1.6 to 7 ft) in diameter and 30 to 60 m (100 to 200 ft) long. These historical sizes indicate the potential maximum sturdy-log length that could eventually result from reduced bank clearing and snag removal.

Design Log Length and the Span Length of Existing Bridges

Potential is low for blockage of spans with effective width greater than the design log length. Most span blockages have involved spans with an effective width less than the design log length. Exceptions have involved other factors such as sediment accumulation or drifting objects larger than logs such as cabled log rafts.

The design log length, which is also the minimum effective span length for low trapping potential, is intentionally set at the highest level justified by the set of confirmed pier-to-pier accumulations. Additional research may identify situations in which span lengths with low potential for drift trapping are below this threshold. Risk should be balanced against cost in deciding whether this threshold should be modified or used in designing bridges (Pangallo and others, 1992). The cost of designing for drift lies outside the scope of the present study. However, the available data indicate that this threshold span-length is probably not too low. In other words, spans longer than this threshold value belong to a set of spans in which bridging from pier to pier by drift is rare or absent.

A large percentage of existing bridges have spans short enough to be blocked by drift. The 10,352 selected bridges used in the scour-potential studies in Indiana, Maryland, South Carolina, and Tennessee show how the percentage of bridges with spans shorter than the maximum length for span blockage can vary with channel width and from State to State (table 3). About half the selected bridges have spans shorter than the design log length. Variability among States reflects differences in criteria used to select potentially scour-critical bridges for inclusion in the scour-potential studies.

Depth, Shape, and Structure of Drift Accumulations

Most drift accumulations form at the water surface as a raft. Logs and smaller pieces of drift accrete to the upstream edge of the raft. The accumulation can grow toward the river bed through accretion of logs on the underside of the raft as they are washed under it by the plunging flow at the upstream edge. Alternatively, the raft can become thicker by collapsing in compression along the direction of flow as the lateral hydraulic forces on the raft exceed its compressive strength (Kennedy, 1962). Drift accumulations are typically deepest at the piers that support them, and widest at the surface. The potential to achieve a roughly rectangular cross section (transverse to approaching flow) from the bed to the water surface may be related to abundant drift, prolonged periods of high water, or multiple floods without intervening drift removal.

The depth of a blockage is limited by the depth of flow. Several observed drift accumulations extended upward nearly to the maximum flood stage even after the flood receded. Allowing for compression of the jam as the water level dropped, these accumulations likely occupied the entire depth of flow. The maximum vertical extent of drift observed in this study was about 12 m (40 ft), but a larger vertical extent of drift seems possible. Australian and New Zealand's design practices incorporate limits to the vertical extent of drift accumulations, but the basis for selecting such limits is unclear (National Association of Australian State Road Authorities, 1976; Apelt, 1986a; Wellwood and Fenwick, 1990; Dr. Arthur Parola, University of Louisville, written commun., 1992).

Accumulations may be irregular, but most large accumulations are similar in shape. Logs are initially trapped perpendicular to approaching flow in most accumulations, but as accretion continues, logs are added parallel to the upstream edge of the raft. Accretion is fastest where the path of most drift in the river intersects the accumulation. The net result is often an accumulation with a curved upstream edge, and with the upstream nose of the raft near the thalweg. Drifting logs encountering the nose, where the edge of the raft is perpendicular to the flow, are more likely to be trapped at the upstream edge of the raft, or swept under it, than logs that encounter the edges diagonal to the approaching flow.

Table 3. Percentage of selected bridges having spans shorter than the design log length.

State	Number of selected bridges	Percentage of selected bridges with spans shorter than the design log length			
		Range of channel widths			All channel widths
		0 to 12 m	12 to 60 m	60 to 300 m	
Indiana	2,394	20	32	38	25
Maryland	879	43	45	59	46
South Carolina	3,498	45	78	68	56
Tennessee	3,581	65	75	80	72
All four States	10,352	42	64	68	53

The sides of an accumulation may be trimmed by the breakage of protruding logs. This effect is most noticeable where water velocities are high, as at bridges where most of the channel is blocked by drift.

Drift accumulations originate at the water surface, but ultimately become part of the streambed. As the water level rises during a flood, drift already on the bridge generally remains in place as new drift continues to be added at the water surface. When the water level falls, accumulated drift typically slides downward on the pier or piers in contact with it until it rests on the bed. Most accumulations do not float to the surface during subsequent floods, but form a solid mass with irregular protrusions around the base of the pier or piers against which they rest.

Drift accumulations typically begin as loose accumulations of multiple logs; eventually, the gaps between logs fill with branches, twigs, and leaves. Sediment fills some of the remaining voids in the accumulation. This mass of wood and sediment may persist indefinitely, potentially forming a base for further accumulations.

Effects of Pier Type and Placement

Pier placement can result in a high potential for single-pier accumulation even if the span length is above the threshold value for low span-blockage potential. A pier in the path of drift will likely trap it. Along the Harpeth River, Tennessee, even bridges with long spans and round pier noses were subject to single-pier accumulations. In addition, if the effective span width from a poorly placed pier to the bank is smaller than the threshold value for span length, potential for accumulations across the gap between the pier and the bank will also be high. In a narrow channel, a single pier near the center of the channel may have high potential to initiate a channel-wide drift accumulation.

Piers on the banks are less likely to trap drift than piers in the channel. Among 3,581 selected bridges in Tennessee, those with one pier in the channel were several times more likely to have single-pier drift accumulations than bridges with two piers on the banks and none in the channel.

Like the potential for single-pier accumulations, the potential for span blockages depends on pier placement, channel curvature, and other channel shape features. In relatively narrow channels with one or two piers in the channel, placement of piers at or near the bank bases seems to create less potential for span blockage than placement in the main channel. Where the reach upstream from the bridge is a long curve, drift is likely to move along the outer (concave) bank, and a span from the outer bank across much of the channel probably has the lowest trapping potential for a given span length. Where the reach upstream is a long, straight channel segment and the channel banks are wooded down to the bank bases, a span over the center of the channel likely has lowest trapping potential. In any situation where most drift follows a relatively narrow path along the surface of the stream, and piers are located outside of this path, span blockage is somewhat less likely. Thus, pier placement is an important factor regardless of whether span length is above or below the span-length threshold for high trapping potential.

Several pier types aggravate the potential for trapping drift. Multiple columns can act as a sieve unless exactly aligned with flow. The gaps between columns are narrow relative to drift length, and logs spanning the gap between two or more columns can be firmly held. Logs can become entangled in a group of columns in ways not possible at a single-column pier. Of the bridges included in the Tennessee scour-potential study, those with skewed pile bents in the water were about twice as likely to have drift on them as those with unskewed bents in the water.

Where clusters or multiple rows of piles are exposed to drift, accumulation is likely (figure 26). This situation can result from the intentional placement of a footing above the water surface in the channel, or from the exposure of piles through erosion.

The flat noses of rectangular piers and pier footings also can provide stable resting places for drift. A square nose supports trapped drift at both vertical corners, which are sometimes widely separated. The accumulation must rotate around one of these points to become dislodged from the pier.

Some existing design recommendations favor rounded pier noses over sharp noses. Drift may slide more easily along a rounded pier nose, increasing the ability of the round-nosed pier to shed drift. However, selected Tennessee bridges with round-nosed piers were not significantly less likely to accumulate drift than bridges with sharp-nosed piers.

Figure 26. Downstream side of a pile cluster with accumulated drift.

Chronic Accumulations and Countermeasures

Drift accumulation is chronic where abundant drift is frequently delivered to piers or spans that have a high trapping potential. Chronic accumulation repeatedly subjects the bridge to the ill effects associated with drift. Drift-removal cost may become a significant component of total bridge cost during the life of the structure (Pangallo and others, 1992). Although prompt and complete drift removal is the most commonly used countermeasure, structural means of guiding drift through bridge openings have been applied at some sites. Scour countermeasures such as river-training structures and bed and bank armor may also be effective drift countermeasures.

The potential for accumulations to grow over the course of two or more floods depends on the difficulty of drift removal. At bridges where removal is difficult or expensive, accumulations are likely to remain in place longer. For example, at State Route 59 on the Eel River near Clay City, Indiana, at State Route 59 on the Vermilion River near Cayuga, Indiana, and at Sneed Road on the Harpeth River of Tennessee, accumulated drift accessible from the banks had been removed at the time of the visit, while drift in the center of the channel remained in place. The presence of drift accumulations from previous floods can have several consequences. A pier with accumulated drift on it may shed additional drift less effectively than if it were bare. An accumulation developing on top of a previous accumulation grows more rapidly through interaction with the drift below it. Drift remaining on the bridge has the potential to promote the growth of an island or bar.

The use of long spans allows the bridge designer to place fewer piers in the water, and makes it easier to avoid placing piers in the path of drift or near the center of the channel, where access is most difficult. Long spans, especially those longer than the design log length, are less likely to be blocked by drift. Because of these advantages, the use of long spans should decrease the frequency and difficulty of drift removal.

Wall piers that extend upstream to the edge of the parapet are easier to clear than piers of other types. Drift not only accumulates more readily on multiple-column piers, but also may become entangled with the columns along the full width of the underside of the bridge, possibly creating access problems for drift-removal crews. Drift trapped on trusses and piers with multiple columns can be entangled among multiple structural elements. Entanglement makes removal more difficult and adds to the possibility of damage to the bridge during clearing operations. Hammerhead piers are an alternative to multiple columns, but have the disadvantage of placing the pier nose well under the bridge and making it difficult to lift drift off the top of the accumulation (figure 27). At worst, drift may fill the space between the overhang of the pier and the bed, causing even more difficulty.

Superstructures that allow access to the pier nose from directly above ease drift removal. At best, a crane or log-picker operated from the bridge deck during the flood can remove drift before it forms an entangled accumulation (Rowe, 1974; Turner, 1992). A wide deck with a simple parapet and adequate load-bearing capacity for heavy equipment at the upstream edge affords the best opportunity for drift removal from the deck.

Access to the substructure of the bridge is important in allowing prompt and complete drift removal. Tracked vehicles may be able to remove all drift from a small channel during low water. On large rivers, access for barge launching may be needed.

Drift accumulation can be prevented where drift is accumulated upstream from the bridge, deflected away from piers, or guided through wide openings. Various measures to collect or guide drift have been suggested by several sources (Brice and others, 1978a; Lagasse and others, 1991; Richardson and others, 1991). Effective drift deflectors at two sites are mentioned by Lagasse and others, but no locations or designs are given. In their compilation and analysis of scour problems and countermeasures, Brice and others (1978a) provide the location of one deflector that failed, and have this to say about countermeasures in general:

> "Except for well-known design features relating to bridge clearance, pier spacing, and in particular to webbing or enclosure of multiple column piers or pile bents, no successful devices for the prevention of debris accumulation were reported in the interviews."

Figure 27. Drift under the upstream side of a bridge deck.

A laboratory study of floating booms includes recommendations for glance booms as deflectors for pulpwood in currents of 1.4 meters per second (4.6 feet per second) or less (Kennedy and Lazier, 1965). The design depends on a smooth, vertical face at a small angle to the approaching flow, with a horizontal lip projecting upstream to prevent pulpwood from being carried under the boom by the strong induced current plunging under it. Pulpwood logs 1.2 to 2.4 m (4 to 8 ft) long (the range considered by Kennedy and Lazier) would float above this lip. The larger size and greater irregularity of logs that include branches and root masses might reduce the effectiveness of this design. No recommendations are offered for mooring such a boom in water subject to large changes in stage. No field experience with such designs is mentioned.

Perham mentions several deflection booms used in reservoirs and one in the Clark River in Idaho (Perham, 1988). These booms have smooth, vertical, upstream faces, but no horizontal lip is mentioned. Deflection booms work best when the angle to the flow is 20 degrees or less. Water velocity and depth are important considerations in boom design, but values of depth and velocity at effective booms are not given. Other effective deflectors include steel barges moored or sunk at a small angle to the approaching flow.

McFadden and Stallion (1976) recommended the installation of a system of pilings intended to align logs to pass through a set of gates 7.6 m (25 ft) wide at a dam on the Chena River in Alaska. These pilings were installed, and a model test of their ability to align drift was performed. Results were inconclusive:

> "In many cases [the pilings] aligned the model logs so that they passed through the structure without incident. However, in some instances the model logs would form jams around the pilings. Clearly more work is needed to determine if these pilings are of sufficient value to warrant their installation." (McFadden and Stallion, 1976)

River training may prevent skew at multiple-column piers, thus reducing their tendency to trap drift. By stabilizing the channel location at the bridge, river training may keep piers in appropriate locations to avoid contact with drift in the zone of surface convergence. Any measures that stabilize the upstream channel will also reduce the supply of drift to the channel.

Effects on Bridges

Drift has always been an important cause of bridge failures in the United States, especially in earlier years when quantitative hydrologic information was scarce and the importance of scour was not recognized (Edwards, 1959). The high design-discharge capacity, massive structure, and sturdy foundations typical of modern bridges help them withstand the effects of drift, but drift has remained a significant cause of failure and other damage (Chang, 1973).

Scour is the leading concern related to drift, followed by lateral forces (Pangallo and others, 1992). The presence of drift enhances pier and contraction scour. At most bridges identified as having drift problems, scour was the cause of damage or failure. In many cases, this scour occurred away from the drift accumulation.

Accumulated drift, acted upon by flowing water, exerts significant forces on piers and superstructures. At some bridges where flood waters reached the low chord of the bridge, drift forces were blamed for serious damage independent of scour effects (O'Donnell, 1973; Gannett Fleming Corddry and Carpenter, Engineers, 1974; Brice and others, 1978a; Chang and Shen, 1979). Forces exerted by drift on piers in combination with scour may have contributed to several pier failures.

The impact forces produced by drift striking bridges, and road overflow associated with drift accumulations, are less important effects of drift. Drift impact typically produces minor damage. Loss of conveyance in the bridge opening due to drift accumulation increases flood stages, road overflow, and embankment erosion.

Drift-Related Scour

Based on the cited case studies, scour associated with drift accumulation is the most common cause of bridge failure that involves drift. However, few studies of scour consider drift. Because the size, shape, location, roughness, and porosity of drift accumulations are highly variable, the effect of drift on scour is likewise variable (Laursen and Toch, 1956; Highway Research Board, 1970; Makowski and others, 1989; Richardson and others, 1991; Sherrill and Kelly, 1992; Becker, 1994). The potential for drift accumulation is relatively high for the design discharges (100-year, 500-year, and minimum overtopping discharge) used in the analysis of potential scour in the United States. Limited computer modeling of drift-related scour shows that drift can have a significant effect on scour, as well as on bridge-backwater effects (Prasuhn, 1981).

Scour associated with naturally accumulated drift is difficult to measure and has been measured at only a few sites (Becker, 1994). A few physical model studies of scour related to drift have been performed (Laursen and Toch, 1956; Foster, 1988; Dongol, 1989; Sterling Jones, Federal Highway Administration, written commun., 1996).

In this study, scanning sonar was used at the FM 2004 bridge over the Brazos River near Lake Jackson, Texas to observe scour around a large single-pier drift accumulation near the peak of a major flood. The drift accumulation extended from the bed to the surface, and had a maximum width of about 23 m (75 ft). Flow approaching the pier had a depth of about 8 m (25 ft). The maximum depth just upstream from the drift accumulation was about 11 m (35 ft), and under the spans adjacent to the accumulation the maximum depths were 12 m (40 ft) and 14 m (45 ft). Thus the maximum scour depth was about 6 m (20 ft) relative to the bed of the river upstream from the drift accumulation. The deepest scour occurred next to the

widest lateral extensions of the accumulation, and evidently was a combination of local and contraction scour.

Laursen and Toch (1956) studied the effect of drift accumulations on scour in sand around the foot of a model pier 0.06 m (0.2 ft) wide. Their models of drift accumulations included accumulations of floating twigs allowed to form in the flume, bundles of twigs tied with string, and flat pieces of masonite fixed perpendicular to the flow. They found that drift increased scour depths except in the case of buried drift around the base of the pier. They did not attempt to quantify this effect, and concluded that:

> "Debris, in effect, enlarges the pier and thus results in increased scour depths and areas. The difficulty in evaluating even qualitatively the effect of debris is that the permeability and the position are as important as the overall size of the debris mass." (Laursen and Toch, 1956)

Hopkins and others (1980) used the concept of effective pier width. Their study used field data from a pier in the Brazos River that characteristically had drift lodged in the piling cluster. They estimated that the effective width of the pier was approximately doubled by the addition of "complete debris buildup" to the footing and piling cluster. However, the authors were not able to measure actual drift accumulations and compare them to the corresponding measured scour depths.

Using the facilities of the Hydraulics Laboratory of the U.S. Army Engineer Waterway Experiment Station, Foster (1988) performed a model study of scour around a large drift accumulation on a large construction trestle in the Mississippi River. The drift accumulation had an area of about 4 hectares (10 acres), a width perpendicular to the flow of about 240 m (800 ft) (the full length of the work trestle), and an unknown thickness, assumed in the model study to be either 2.7 or 5.5 m (9 or 18 ft). The drift was simulated in the model by a layer of rubberized hair material. Based on the model study, the drift caused as much as 6 m (20 ft) of bed scour under the trestle and doubled the depth of local scour around cofferdams.

Dongol (1989) conducted a flume study of scour in sand around a cylindrical pier, using solid wooden shapes fixed to the pier. The models used were various cylindrical disks, an elliptical disk, and an inverted cone. Dongol also modeled drift accumulation around the pilings below the footings of the Wairoa Bridge in New Zealand, using foam rubber held in place by wire netting. Presence of drift at the surface increased scour depth and downward velocity at the pier nose. Dongol gives an equation for calculation of effective pier width and suggests that maximum scour is 2.3 times the effective pier width (Melville and Sutherland, 1988; Melville and Dongol, 1992). Based on field reports and case studies, he notes that drift trapped on piers is forced downward and that ultimately the effective pier width may be equal to the width of drift. This implies that the maximum scour depth "could be anticipated to be" 2.3 times the width of the drift accumulation. However, some of Dongol's models of large drift accumulations caused deposition around the pier, rather than scour. Thus, this maximum anticipated depth is not invariably the result of a large accumulation.

Scour may occur beneath or upstream from a drift accumulation, or away from the drift where increased flow velocity results from constriction of the bridge opening or deflection of the flow (Laursen and Toch, 1956; Klingeman, 1971; Klingeman, 1973; Rowe, 1974; Shen and others, 1981; Foster, 1988; Richardson and others, 1991; Becker, 1994). Downward vertical velocity is important in determining scour depth (Tison, 1961; Dongol, 1989). The presence of disks or plates near the base of a vertical pier reduces scour depth by interrupting downward flow (Tanaka and Yano, 1967; Thomas, 1967). The presence of drift at the base of a pier can also reduce scour depths near pile footings, probably in a similar manner (Laursen and Toch, 1956; Dongol, 1989; Sterling Jones, Federal Highway Administration, written commun., 1996). General scour and deflected flow are common where piers constrict the channel, and vortices at adjacent piers interact to produce additional scour (Blodgett, 1984; Elliot and Baker, 1985). Drift accumulations may increase these effects. Deflected flow may increase the velocity and skew at adjacent piers. Scour associated with drift can include removal of riprap as well as movement of natural bed material (Linder, 1967; Klingeman, 1973).

Drift accumulations at bridges promote several types of channel change. Sedimentation may occur among the logs of a drift accumulation and in the eddy just downstream, producing a bar surrounding a pier or in the eddy just downstream. Steep-faced lingulate bars were observed downstream from span blockages, representing the deposition of material transported under these accumulations or scoured from beneath them. Bars were also observed in the divergent, decelerating flow upstream from the area of local scour at the upstream edge of drift accumulations. Channel widening may expose piling clusters or skewed pile lines formerly on or in the bank. Channel migration promoted by drift may increase skew and thereby worsen the potential for drift accumulation. It has been observed that blocking more than 5 percent of the channel cross section with piers may cause scour (Blodgett, 1984). Even a small drift accumulation can exceed this threshold size; such accumulations are common at selected scour-potential-study bridges (table 4).

Drift-Related Forces

Forces exerted on bridge decks and superstructures by drift accumulations have caused displacement of bridge spans and damage to piers. Simply supported trusses are most vulnerable to this kind of damage (O'Donnell, 1973). The sieve-like structure of the truss acts as a trash rack, and spans are not designed to resist the resulting lateral forces. Forces

Table 4. Percentage of channel blocked by drift at selected scour-potential-study bridges.

Percentage of channel blocked		Number of selected bridges, by State				
Greater than	Less than or equal to	Indiana	Maryland	Massachusetts	South Carolina	Tennessee
75	100	3	1	0	35	6
50	75	2	1	0	28	18
25	50	28	7	1	100	74
5	25	104	51	16	409	282
0	5	133	62	37	481	422
	0	2,124	757	702	2,445	2,779
Total number of bridges		2,394	879	756	3,498	3,581
Percentage of channel blocked		**Percentage of selected bridges, by State**				
Greater than	**Less than or equal to**	**Indiana**	**Maryland**	**Massachusetts**	**South Carolina**	**Tennessee**
75	100	0.1	0.1	0.0	1.0	0.2
50	75	0.1	0.1	0.0	0.8	0.5
25	50	1.2	0.8	0.1	2.9	2.1
5	25	4.3	5.8	2.1	11.7	7.9
0	5	5.6	7.1	4.9	13.8	11.8
	0	88.7	86.1	92.9	69.8	77.5
Total of percentages of bridges		100.0	100.0	100.0	100.0	100.0

on piers due to drift have also contributed to failure by placing additional forces on piers subjected to scour (O'Donnell, 1973; National Transportation Safety Board, 1990; I. Nagai, California Highway Department, written commun., 1992; James Schall, written commun., 1993).

Published work on drag coefficients of drift accumulations at bridges is limited to studies of idealized models of drift accumulations (Apelt, 1986a). The drag coefficient varied significantly with variations in the porosity and internal structure of the drift. Apelt (1986a) recommended studies of drag forces on real drift accumulations. Such a study is now underway (Thomas Fenske and Arthur Parola, University of Kentucky, written commun., 1995). Other studies have used flume experiments and field measurements to estimate drag coefficients for drift accumulations away from bridges (Shields and Smith, 1991; Gippel and others, 1992; Shields and Gippel, 1995).

Drift Impact

Impact of individual pieces of drift on bridges has been cited as a cause of damage, especially to the upstream pile in a bent (Chang, 1973). Drift impact alone, however, has caused few bridge failures (Bowser and Tsai, 1973; National Transportation Safety Board, 1990). In the case of the failure of the temporary Harrison Road bridge over the Great Miami River at Miamitown, Ohio, an eyewitness reported that a large mass of drift including a boat and part of a dock collided with the pier (which already had a drift accumulation on its nose) and that the pier then failed (National Transportation Safety Board, 1990). This failure may have been due primarily to impact forces. In other cases, the cause of failure is not well documented (Bowser and Tsai, 1973). A study of actual forces due to drift impact is now underway (Thomas Fenske and Arthur Parola, University of Kentucky, written commun., 1995).

Road Overflow

Loss of flow capacity in the bridge opening may greatly increase flood depths upstream (Williams, 1990). Resulting overflow of approaches may protect the bridge itself from structural damage, possibly at the cost of embankment erosion (O'Donnell, 1973). Increased backwater is combined with increased hydrostatic forces on the drift accumulations, increased flow velocities and contraction scour, and an increased chance that the superstructure will become immersed.

Suggested Guidelines for Assessment of Drift Potential

These guidelines summarize current knowledge about drift, and are an example of one method of assessing the potential for drift accumulations on specific parts of a bridge. The factors used in this assessment may not be the only factors significantly influencing drift accumulation, and this is not the only way in which they can be combined. The use of these guidelines requires engineering judgment and should be tempered by regional experience with drift problems.

The assessment of potential for drift accumulation at a bridge can be divided into three major phases. First, estimate the potential for the stream to deliver abundant drift to the bridge site, along with the likely maximum dimensions of individual pieces of drift, and divide the site among location categories that define the local potential for drift delivery. These location categories reflect site characteristics and do not depend on the bridge design. Secondly, evaluate the bridge characteristics that influence potential for trapping drift at individual piers and spans, and integrate the potential for drift delivery with drift-trapping characteristics to obtain estimates of potential for drift accumulation at individual piers and spans. Finally, combine potential for accumulation on individual elements of the bridge to estimate potential accumulations for the entire bridge. These three phases can be further divided into eight tasks (table 5).

Potential for a River to Deliver Drift

The potential for a river to deliver drift combines the potential for wood to be introduced into the channel and the potential for drift to be transported downstream to the bridge site. Information gathered to aid in the assessment of drift may bear on potential for drift generation, drift transport, or both. Some information is direct information about large woody debris and drift. Other information about the stream and its basin has implications for drift generation and transport. Direct evidence should be evaluated first and given greater weight than indirect evidence (figure 28).

Direct Evidence from Observed Drift

Observations of drift provide the most direct evidence for assessing potential for drift delivery to a site. However, a lack of drift at the site does not indicate a low potential for drift delivery (Pangallo and others, 1992). Observations of drift may come from bridges or from other sites of accumulation, and from the channel system upstream from the site or from channel systems in similar basins. Even if drift is currently sparse, infrequent catastrophic events or changes in the basin may provide abundant drift in the future.

Direct evidence for high delivery potential includes the following observations:

- Multiple cases of drift accumulation at bridges.
- Chronic drift accumulation at one or more sites.
- Drift accumulation at sites where potential for drift accumulation would be low if drift were not abundant.
- Abundant drift in the channel.
- Past need for drift removal in the channel system.

Direct evidence of currently low drift delivery, suggesting possible low potential for drift delivery, includes the following observations:

- Negligible drift after floods at sites with high potential to trap drift.
- Negligible drift delivered in large floods, ice storms, and wind storms.
- Drift absent after floods in typical drift-accumulation sites other than bridges.
- All drift accumulates in forested channel upstream.
- Drift in the channel is stationary during floods because of low flow velocity.

Table 5. Major phases and tasks in evaluating potential for drift accumulation at a bridge.

Major Phase	Tasks
1. Estimate potential for drift delivery.	a. Estimate potential for drift delivery to the site. b. Estimate size of largest drift delivered. c. Assign location categories to all parts of the highway crossing.
2. Estimate drift potential on individual bridge elements.	a. Assign bridge characteristics to all immersed parts of the bridge. b. Determine accumulation potential for each part of the bridge.
3. Calculate hypothetical accumulations for the entire bridge.	a. Calculate hypothetical accumulation of medium potential. b. Calculate hypothetical accumulation of high potential. c. Calculate hypothetical chronic accumulation.

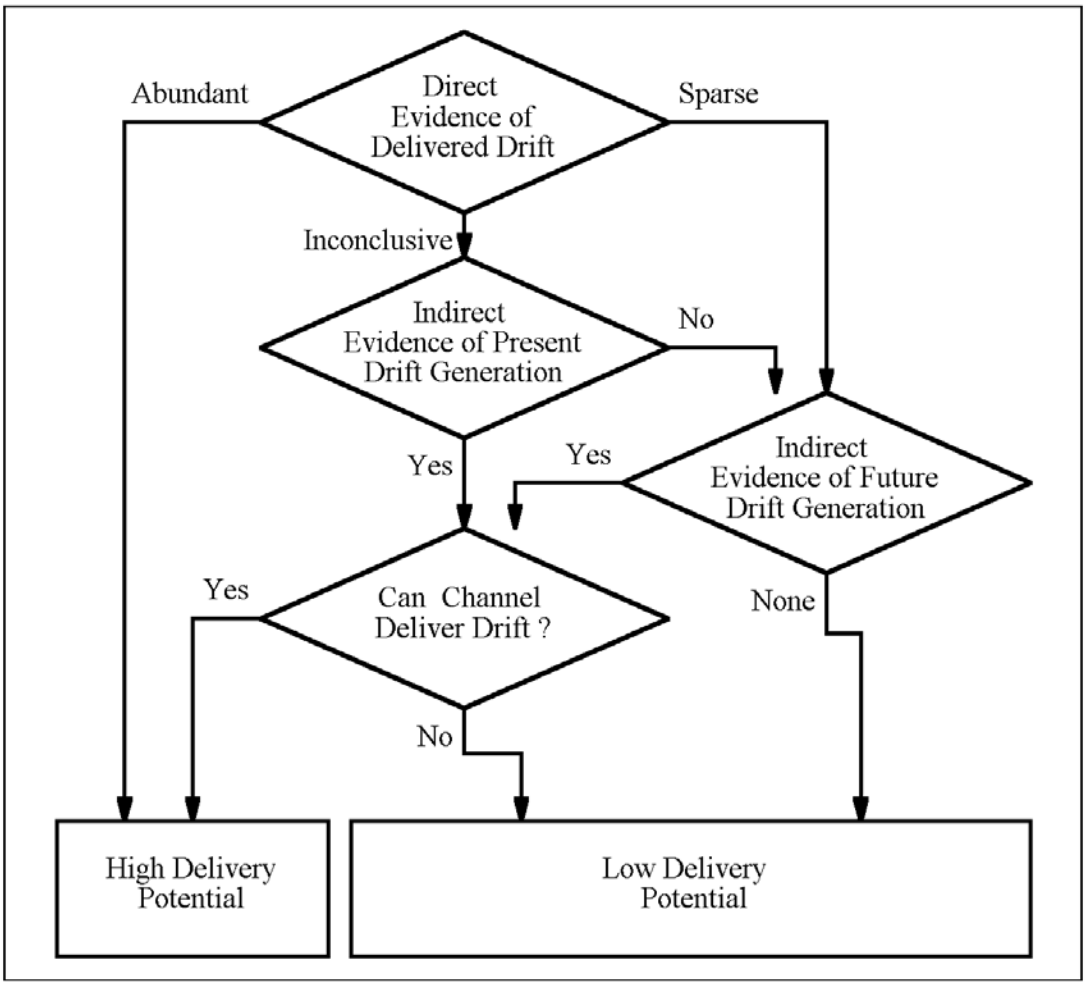

Figure 28. Flow chart for evaluating potential for drift delivery.

Indirect Evidence

Information that does not bear directly on the presence or absence of drift may be useful in assessing potential for drift delivery to a site, but always requires a large element of subjective judgment as part of its application. Such information can bear on drift generation, transport, or both. If the potential for generation can be determined to be low, then the potential for drift delivery is also low. If abundant drift is generated, the ability of the stream to transport drift and the maximum dimensions of drift that can be transported determine the potential for drift delivery.

Indirect evidence of drift generation

Trees introduced into the channel by bank erosion are the dominant type of large drift at most sites. Consequently, most indirect evidence regarding drift generation is evidence of existing or potential bank erosion. Basins containing bridges with chronic drift accumulation generate drift continuously or during annual high-water periods. Most basins have a high potential to generate drift in infrequent, catastrophic events such as large floods, ice storms, and intense wind storms.

Indirect evidence for abundant drift generation includes the following observations:

- Widespread bank erosion in the upstream channel system.
- History of changes in the channel system upstream from the site, including downcutting, lateral migration, widening, channelization, widespread drainage, or dams.
- Prospects of changes in the channel system.
- Hydraulic and geomorphic factors indicating stream instability (Brice and others, 1978a; Lagasse and others, 1991).
- Widespread timber harvesting in the basin.
- History or prospect of marked changes in basin land use.

Indirect evidence for low potential for drift generation includes the following observations:

- Woody vegetation unable to grow along the channel system and on steep slopes leading down to stream channels.
- Channel system fully stabilized, and unlikely to undergo significant change.

Indirect Evidence of Drift Transport

If indirect evidence suggests that the rate of drift generation is high, or could become high, the potential delivery of drift will be controlled by the ability of the stream to transport it. Most streams are capable of transporting some drift. Assume that a given stream can transport drift unless evidence shows that drift accumulates where it is generated, rather than being transported downstream. Forested channels (where trees are numerous and dense across the channel bottom) transport little drift, and can be assumed to have low potential for delivery of drift as long as the forest is not cleared.

Channel dimensions upstream from the site, particularly channel width, affect the size of drift that can be transported, and thereby influence the potential size of accumulations. The width and depth of the channel upstream from the site may increase over the life of the bridge. Indicators of potential increases should be taken into account when estimating future dimensions. Such indicators include: a history of channel migration, widening, or down-cutting; existing or planned dams; and history or prospect of human alteration of the channel network. Erosion-resistant bed and bank material may limit future channel evolution, and effective channel stabilization may prevent future widening and deepening.

The length of transported drift exceeds the channel width in some situations. Where deep water flows unimpeded by forest over the width of a valley, the width and depth of the valley-wide flow control transported-drift dimensions. Deep valley-wide flow is most common in relatively steep, narrow valleys subject to infrequent, large floods. In V-shaped valleys with slopes of 3 percent or more, debris torrents are capable of moving full-sized logs, uprooting or shearing off mature trees, and incorporating them as additional drift.

Estimate the maximum design log length on the basis of channel width upstream from the site. Channel width is the perpendicular distance between banks or lines of permanent vegetation, and it should be measured at inflection points between bends (Lagasse and others, 1991). The longest logs in wide channels reach a maximum length of about 24 m (80 ft) in much of the United States. Channels less than 12 m (40 ft) wide transport logs equal in length to the upstream channel width. In channels in the Eastern United States from 12 m (40 ft) to 60 m (200 ft) wide, the estimated design log length is 9 m (30 ft) plus one quarter of the channel width (figure 24).

A relatively shallow channel may transport logs of a shorter maximum length than would be estimated on the basis of channel width. The depth sufficient to float logs is the diameter of the butt plus the distance the root mass extends below the butt, or roughly 3 to 5 percent of estimated log length. Therefore, the length of transported logs with attached root masses rarely exceeds about 30 times the maximum flow depth; larger logs accumulate in the channel. If flow deep enough to float large logs off the bed can occur, however infrequently, large logs stored in the channel may eventually be transported.

Locations on Site with Respect to Drift Delivery

The delivery of drift at a highway crossing is localized. Some areas of a site may be entirely free of drift transport, while others receive concentrated delivery of drift. Evaluate the potential for drift delivery at each pier and span (figures 29 and 30).

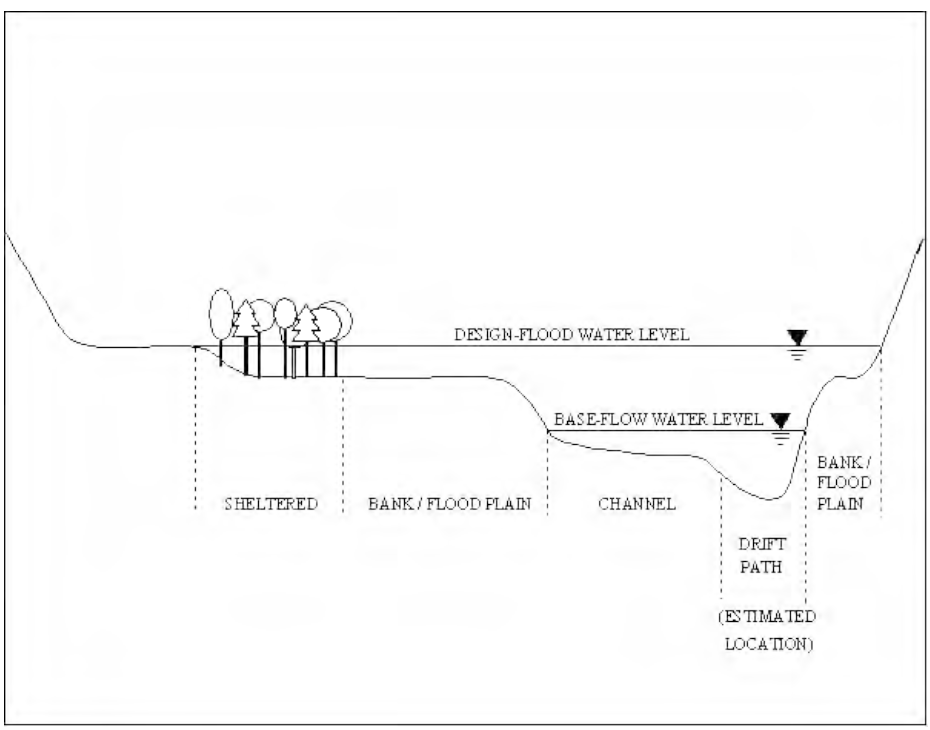

Figure 29. Location categories relative to local drift delivery.

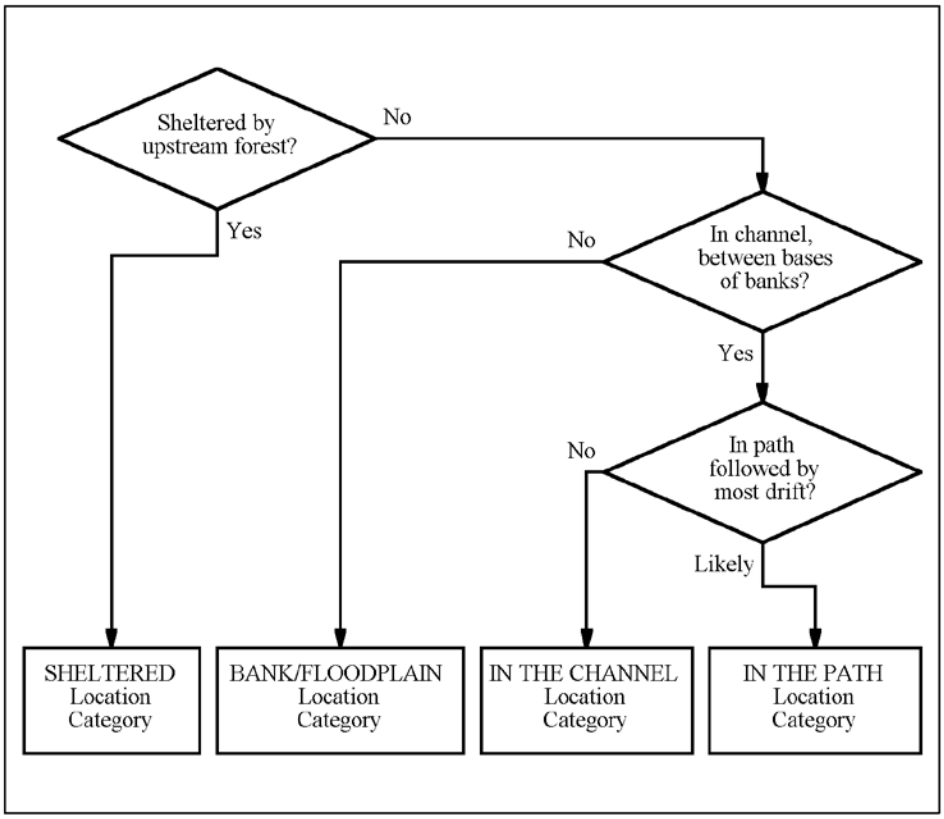

Figure 30. Flow chart for determining location category.

Sheltered by Protected Forest Upstream

In a sheltered location, forest lying directly upstream traps transported drift and prevents its delivery to the bridge. Use this category where gaps between trees are much narrower than the average tree height and the width of forest along the direction of flow is more than a single or double line of trees as along a fence line or river bank. If upstream forest is potentially subject to clearing, select a location category assuming the forest's removal.

Flood Plain, Bank Top, and Bank Slope

For the purpose of estimating local potential for drift delivery, group the flood plain, bank top, and bank slope together in a single location category. Locations in this category may be either forested but subject to future clearing, or presently clear of trees. Flood plain includes any area outside the channel inundated in the design flood to a depth sufficient to transport drift. Piers on bank slopes are not significantly more likely to accumulate drift than piers on the flood plain.

In the Channel

Drift can be transported anywhere in the channel, and drift accumulations are more common in channel locations than on banks or flood plains. USGS studies of scour potential have been conducted in humid regions. These studies have defined locations "in the channel" as those in the water when the bridge was inspected, ideally during base flow (Huizinga and Waite, 1994; Bryan and others, 1995). In arid regions, where base flow is relatively low, designate all locations between the bank bases as "in the channel." Anywhere below the top of the bank, judgment is involved in deciding whether an element of the bridge is in the channel. If evidence indicates that drift is delivered to some location below the bank top, assign that location to the "in the channel" category.

In the Path of Concentrated Drift Transport

In most streams, secondary circulation currents converge at the surface, causing floating material to be transported along a relatively narrow drift path within the channel. Piers located in the drift path are the most common sites of drift accumulation. Such a drift path can be defined in most streams based on observations of small floating material if logs are absent. If such observations are not available, estimate the location of the drift path based on channel characteristics. The width of the drift path is variable, but for the purpose of design, assume a width one-third the channel width unless observations are available.

In a straight reach, the middle of the drift path typically coincides with the thalweg, the thread of the stream, and/or the center of the channel. In a curving reach, the middle of the drift path generally lies between the thalweg and the outside bank

of the bend. At a sufficiently high flood stage, the drift path no longer remains confined to the channel. Drift following the submerged outside bank may be swept across the high end of a point bar or across the isthmus between meander bends. Surface flow may direct drift into chutes originating at the outside of bends (Damaskinidou Georgiadou and Smith, 1986).

The best way to locate the drift path is to observe it during bank-full or higher flow. If high-flow observations are not available, observations during base flow will likely confirm estimates based on channel characteristics. The location of the drift path may move minimally with changing stage, but will be somewhat different at bank-full than at base flow. Observations need not include large pieces of drift, because all floating material responds similarly to the flow pattern.

If direct observation of the drift path is impossible, assign a location to it based on channel characteristics as described above. If the location of the drift path is indefinite, calculate the drift-accumulation potential under several assumed alternate locations for drift path—for example, the left third of the channel, the middle third, and the right third. If you designate the entire channel "in the channel" and none of it "in the path," you may artificially lower the drift accumulation potential. At worst, drift is scattered evenly over an entire channel, leaving the entire channel "in the path."

If available information indicates that the drift path includes part of the bank or part of the flood plain, call that part "in the path." At high water, the drift path may cross point bars and necks between meanders. It is unlikely to go beyond the meander belt, which is the band of the valley defined by extreme excursions of the meandering channel to the left and right.

Bridge Characteristics

Certain characteristics of a bridge have a strong influence on the potential for drift accumulation. If an existing bridge is the object of study, select values for these characteristics based on the current location and design of bridge components. If these guidelines are part of a design process, use alternative locations and designs to determine how they affect the relative potential for drift accumulations at the new bridge. For each design under evaluation:

1. Assign each of the following to one of the location categories described above:
    - gap between fixed elements of the bridge opening
    - pier
    - abutment base
    - section of superstructure where low steel is wetted by the design flood
2. Determine whether the effective width of each gap exceeds the design log length for the site.
3. Determine whether each pier or superstructure section immersed in the design flood includes apertures that carry flow.

Wide Gaps Between Fixed Elements of the Bridge Opening

A bridge includes one or more gaps through which any drift carried by the stream is intended to pass. Where the width of a gap is less than the length of the longest pieces of drift delivered to it, the potential for drift accumulation can be high. Estimate the effective width of gaps between fixed elements of the bridge opening including piers, banks, and abutments. In addition to the gap between each pair of adjacent piers, assign a width to the gap between each bank and the nearest pier in the channel and the gap between each abutment and the nearest pier. If low steel is submerged in the maximum design discharge, estimate the width of vertical gaps between sections of the superstructure and the streambed or flood plain below them. (Gap "width" as used in this analysis may be the horizontal distance across the direction of approaching flow between projected positions of vertical elements or the vertical distance across the gap between low steel and the streambed.)

Horizontal Gaps

Horizontal gaps are common locations for large accumulations of drift. Piers, nearby banks, and abutment bases are fixed elements of the bridge opening that can interact to trap drift. Pieces of drift in the longest size fraction delivered to the site will typically come into contact with one such element, then rotate downstream until they lodge against another element. Once one log is lodged across a gap at the surface, other pieces of drift can lodge against it and against the bridge, speeding the accumulation process. Alternatively, the horizontal gap may extend from a drift accumulation on one element to another element previously free of drift.

Where the bridge is skewed to approaching flow, the effective width of horizontal gaps is reduced. In order to estimate the effective width, one must first estimate the direction of flow approaching the gap during the design discharge. Project the positions of the upstream noses of fixed elements parallel to this flow direction onto an imaginary plane perpendicular to the flow direction. The effective width of a horizontal gap is the distance between the projected positions of the elements defining it (figure 21).

A horizontal gap should be assigned to the most drift-prone location category occupied by the fixed elements that define the gap. A horizontal gap from a pier to a bank or abutment has the same location as the pier. (For example, if the pier is on the bank slope, the gap is "on the bank." If the pier is in the drift path, so is the gap.) A horizontal gap between a pier on the bank and a pier in the channel should be classified as "in the channel." Where one of the fixed elements is sheltered and the other is not, the gap should be regarded as unsheltered.

Vertical Gaps with Low Steel in the Water

When the water level is at or above the bottom of the superstructure ("low steel"), drift may become trapped vertically between the superstructure and the streambed below it. Most drift is transported at the surface. When floating drift hits the superstructure, most pieces rotate to one side, remaining at the water surface. The drift then accumulates against the superstructure at the surface or is swept under the superstructure. However, some pieces of floating drift hit roughly endwise, and the upstream end rotates downward until it encounters the streambed . Some such pieces remain lodged against the superstructure and the streambed .

The fixed elements defining this vertical gap are low steel and the streambed beneath it. Measure the width of the gap vertically. The height of this gap will vary along the bridge as the elevations of low steel and the streambed change.

The location of a vertical gap can also vary from point to point along the bridge, even within an individual span. A vertical gap from the bank, bank top, or flood plain to low steel is in the flood-plain/bank location category. A vertical gap over the channel belongs to that location category, and a vertical gap at the drift path should be assigned to the "in the path" category.

Pier and Superstructure in Flow: Solid, or with Apertures

The hydraulic characteristics of parts of the bridge exposed to floating drift determine whether drift is deflected or trapped. In this regard, the most important hydraulic characteristic is flow through narrow apertures at the water surface. Piers and superstructures with narrow apertures that carry flow are significantly more likely to trap drift.

Examples of Flow through Pier and Superstructure Apertures

One well-recognized example of flow through apertures occurs with substructures made up of two or more parallel rows of pilings exposed at the water surface. Many such piers are designed as such so that concrete for the footing can be poured above water. Others result from degradation of the river bed below pier footings, or exposure through bank erosion of piles originally buried below the flood plain. In any case, flow through the narrow apertures between piles pins drift against them. When such clusters of piles are skewed to the approaching flow, the increased width of surface flow passing through the apertures brings with it an increased likelihood of drift accumulation.

A pile bent, or a pier made of a single row of cast columns, may be aligned to the approaching flow so that each vertical pile or column is directly downstream from the one furthest upstream and no significant flow passes through the relatively narrow apertures between them. Alternatively, the approaching flow may be skewed to the line of the columns or piles, so that flow passes through each aperture. The width of surface flow passing through the apertures depends on the length of the line of columns or piles and the angle between the line and the approaching flow. Trapping associated with skewed flow through a line of columns is indicated by accumulated drift lying along one side of the line of columns.

Observing the site during high water may be the only way to determine whether approaching flow is skewed or aligned to the pier. The flow direction may change, particularly when stage increases beyond bank-full. Surface flow may cease to be roughly parallel to the banks and become roughly parallel to the valley or meander belt. Flow direction can be altered by bridges that impede flow along part of the valley.

Other changes can cause skewed flow at piers that were originally aligned to flow. If enough drift accumulates on one part of a bridge, flow directions at nearby piers will be altered. Channel evolution can produce dramatic changes in flow direction at a pier.

A drift accumulation has poor ability to deflect additional incoming drift because many logs and branches protrude from the main body of the accumulation. These protrusions are apparently more common at lower velocities, while at higher velocities the protrusions are broken off by collision with other pieces of drift, particularly logs. Where drift delivery is frequent and removal is difficult (for example, where blockages form underneath the bridge deck in mid-channel), assume that drift will be in place at the beginning of a flood, and that this drift accumulation will trap drift regardless of the pier's design.

Superstructures that include apertures at or below the water surface are particularly vulnerable to drift accumulation. Open trusses retain most drift over a wide stage range from low steel up to truss top, and this drift typically becomes entangled in the truss. Simply supported trusses are subject to lateral displacement when the water level is above low steel and drift delivery is high (Chang and Shen, 1979). This is one situation in which lateral forces due to drift may be the primary cause of damage to a bridge.

Open parapets with pillars and rails also incorporate narrow apertures. The vertical extent of these apertures is much less than in a truss, extending from the stage at which flow starts to pass through apertures in the parapet up to shallow submergence of the top of the parapet. Drift can entangle in a parapet but apertures are typically small, and entangling is probably less severe than on a truss. Some arrangements of pier caps, beams, and deck create apertures that carry flow and trap drift. Flow may pass over beams and under the deck. Some arrangements of diagonal bracing create triangular apertures through which flow passes. Some arch bridges include openings between the deck and arches that are too small for logs to pass through.

Examples of Bridge Elements without Flow through Apertures

Many bridges lack small apertures conveying flow. Single-column piers, whether walls, cylinders, or hammerheads, deflect all flow through wide adjacent gaps. A deck

resting directly on solid beams, with a solid parapet, is another example. The apertures in a single row of columns carry no flow and do not contribute to drift trapping if the row is aligned to approaching flow.

Estimating Potential for Accumulation by Location and Type

After estimating the potential for drift delivery to the site and assigning location categories and other bridge characteristics, estimate the potential for drift accumulation separately for each pier, each section of immersed superstructure, and each horizontal or vertical gap between fixed elements.

Estimate potential for drift to span an individual gap between fixed elements of the bridge opening, using the flow chart in figure 31. In addition to the estimated delivery potential, which is the same for the entire site, this flow chart uses two variables that must be selected for each horizontal or vertical gap: effective length of the span between fixed elements relative to design log length (gap wider or narrower), and location category of the gap.

Estimate the potential for accumulation on each pier and section of superstructure, using the flow chart in figure 32. In addition to the estimated delivery potential, which is the same for the entire site, this flow chart uses two variables that must be selected for each pier and section of superstructure: location category, and presence or absence of narrow apertures that carry flow.

Size of Potential Accumulations

Drift accumulations can grow to maximum sizes that depend mostly on log dimensions, flow depth, and the number and proximity of gaps and piers affected. Accumulations in the channel can reach their maximum size during a single flood where delivery is high, but accumulations grow more slowly where the drift supply is low. Large accumulations are less likely to occur in a single flood outside of the channel and at sites where delivery of drift is low.

The values of drift-accumulation potential estimated in the preceding section are relative, and do not address the likely size of an accumulation. For example, a “high potential” for drift accumulation at a single pier indicates high potential for a drift accumulation relative to the potential for accumulation at other piers. Accumulations will not necessarily form on all piers with high potential. If an accumulation does form, its width may be as great as the design log length based on channel width, and it may extend vertically to the depth of flow, or it may be much smaller.

The accumulation of drift on a single pier begins with a single piece of drift at the water surface, and the width of the accumulation may reach the length of the design log. If initially narrow, the accumulation can grow to the maximum width

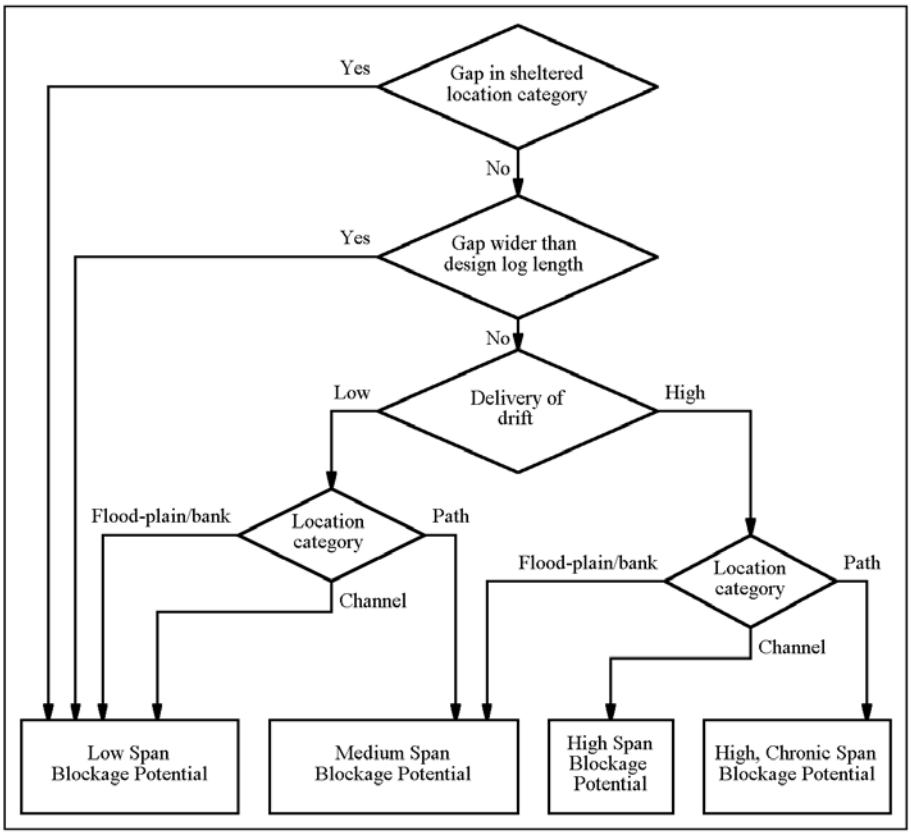

Figure 31. Flow chart for determining potential for accumulation across a span or vertical gap.

through the accretion of a single log. Where drift accumulates across a horizontal gap, the initial accumulation extends the full width of the gap at the water surface, and may ultimately extend beyond the vertical elements defining the gap.

Additional accretion causes the drift accumulation to grow downward toward the streambed. The accumulation can continue to grow downward until it extends over the full depth of flow, with about the same width over its full height.

To be conservative, assume that a drift accumulation extends from the water surface to the streambed. Also assume that an accumulation on a single pier will have a width equal to the design log length over its full depth, and that an accumulation across two or more piers will extend laterally half the design log length beyond them. These assumptions are consistent with the largest observed accumulations, and will probably maximize effective pier width and predicted forces and scour depths. In calculating scour, however, it may be more conservative to assume that an accumulation extends only part of the distance downward from the surface to the streambed.

The maximum size of drift accumulations on superstructures cannot be estimated based on the few existing descriptions of such accumulations. Abundant drift can close all apertures in trusses and parapets as they are submerged. To be conservative, assume that these apertures will be closed. Where drift accumulates across the vertical gap from low steel to the streambed, the entire gap could ultimately be closed. Accumulations on the upstream side of a bridge may extend vertically beyond low steel and the top of the superstructure. The design length used for this vertical extension may have a large effect on estimates of the forces on the bridge and the upstream water level. Data on the distance of vertical extensions are scarce. The Australian design practice of allowing for 1.2 m (4 ft) of total vertical extension above the top of the parapet and below low steel does not seem excessively conservative (Wellwood and Fenwick, 1990).

Effects of Accumulations that Modify Analysis

Drift accumulations change bridge hydraulics and trapping characteristics, and may increase the potential for additional trapping. When all the possible drift accumulations at a given bridge have been assigned a potential for occurrence, alter the assumed bridge characteristics and water levels as needed, then run the analysis again to determine whether some individual accumulations increase in potential. For example, a high-potential blockage across the channel may cause skewed flow through bents in the flood plain, raising the trapping potential at these bents from medium to high. If so, accumulation at these bents should be regarded as having high potential.

Deflection of flow from drift accumulations changes the angle of approaching surface flow at nearby piers. If adjacent piers include multiple columns, assume they are no longer aligned. Also, decrease the effective width of adjacent horizontal gaps as needed to reflect increased skew.

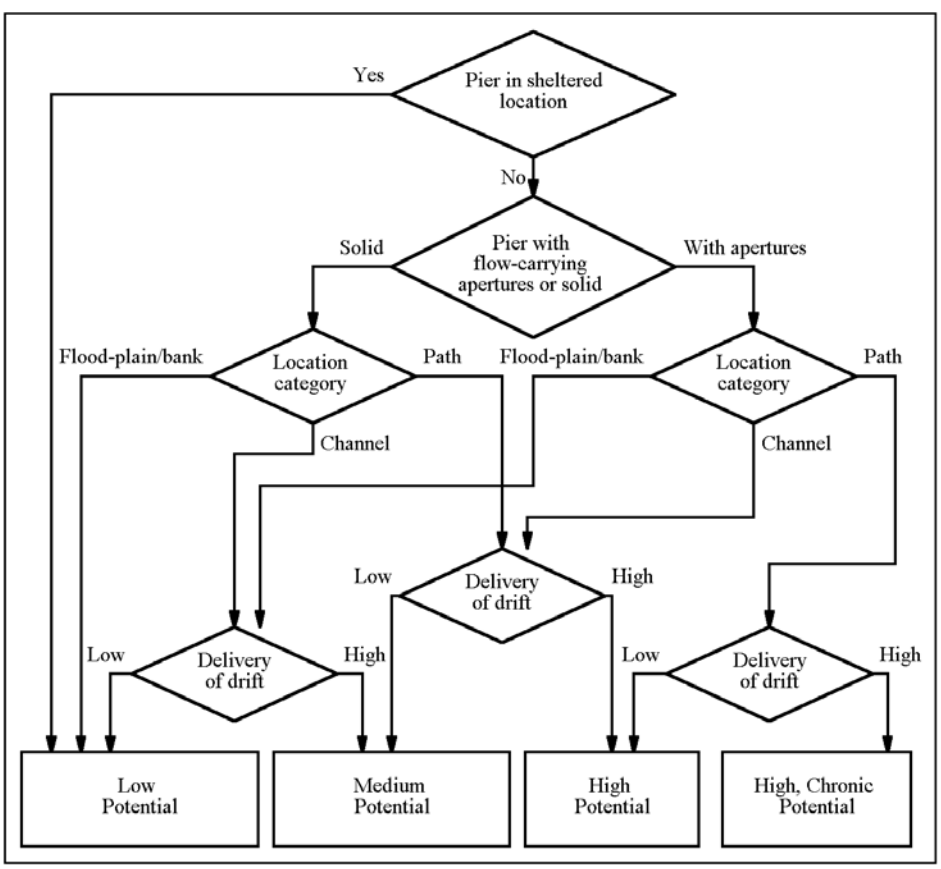

Figure 32. Flow chart for determining potential for drift accumulation on a single pier.

Drift constricts the bridge opening and increases the backwater effect of the bridge. Use a one-dimensional step-backwater flow model (for example, WSPRO) to determine a new upstream water-surface elevation (Shearman and others, 1986; Shearman, 1990). If backwater from drift causes immersion of the superstructure, evaluate the potential for accumulation on the superstructure and across vertical gaps.

Unremoved accumulations change the pier shape to "with apertures" (figure 32). Mid-channel piers in the drift path may retain drift for a long time after it accumulates. This problem is greatest where potential for accumulation is chronic and where the pier is difficult or expensive to clear. Factors impeding removal include a location in mid-channel beyond the reach of cranes on either bank, a pier nose overhung by the deck impeding removal from above, hammerheads with drift wedged under the top of the pier, and multiple columns with entangled drift.

Overall Potential for the Entire Bridge

The potential for drift accumulation at a bridge is the maximum of the potentials estimated for each pier, superstructure section, or gap between fixed elements. For example, if any part of the bridge is assigned a high potential for accumulation, assign the bridge a high potential for accumulation.

The drift accumulation that has a high potential is the sum of all individual high-potential accumulations on single elements or across gaps, assuming each one grows to its maximum size. Similarly, the drift accumulation over the entire length of the bridge that has a medium potential is the sum of all individual medium-potential and high-potential accumulations on single elements or across gaps, assuming each one grows to its maximum size. If the stream frequently delivers abundant drift to the bridge site, combine the individual accumulations assigned high, chronic potential to estimate the location and maximum extent of drift requiring regular removal.

The overall potential for problems related to drift accumulations at a bridge depends on the probability or frequency of events that have the potential to produce accumulations as well as the potential for accumulations to occur at the bridge and the potential size they could reach. An assessment of high potential for drift accumulation could result from assumptions of radical changes in land use in the basin, followed by enlargement of the channel and a large flood. On the other hand, an assessment of high potential could result from the assumed occurrence of a 2-year flood with existing channel conditions. These two assessments would have different implications for bridge design and bridge maintenance.

Conclusions

Drift that accumulates at bridges comes primarily from trees growing on the banks and bank tops of rivers. Most of the trees that become drift are undermined by bank erosion. Rivers with unstable channels have the most bank erosion and the most drift, but some drift is present in most rivers during floods.

Floating drift is concentrated along the thread of the stream and moves at about the average flow velocity. Logs longer than the width of the channel accumulate in jams, or are broken into shorter pieces. Sunken woody debris moves more slowly and tends to accumulate in and along the channel, rather than being transported downstream to bridges.

Drift accumulates against obstacles such as bridge piers that divide the flow at the water surface. Groups of obstacles separated by narrow gaps trap drift most effectively. Drift accumulation begins at the water surface, but accretion can cause an accumulation to grow downward to the streambed. An accumulation on a single pier grows no wider than the length of the longest logs it contains. The gap between two piers is not blocked by drift unless individual logs can reach from pier to pier. Drift damages bridges mostly through local and contraction scour.

Further research on drift is needed in five main areas:

- Compilation of existing data from maintenance engineers, bridge files, and damage reports to identify drift-laden rivers and drift-prone bridges.
- Detailed, three-dimensional measurements of drift accumulations and associated scour in flood conditions.
- Definition of channel types in which drift delivery is low even in floods.
- Refinement of maximum sturdy-log length estimates to reflect regional conditions.
- Identification of spans shorter than the design log length that nonetheless have low potential for drift accumulation.

A large amount of under-used information on drift accumulations remains in bridge files, damage reports, and the memories of active and retired maintenance engineers. Further studies could take advantage of these resources to identify many more drift-laden rivers and drift-prone bridges.

High-resolution scanning sonar has the potential to yield new and valuable information on the size and shape of drift accumulations and associated scour; improvements are needed

in determining the precise location of the sonar transducer relative to the bridge and in discriminating the drift accumulation from backscatter due to turbulence, bubbles, and suspended sediment. Drift accumulations are irregular in shape because of the random accumulation of individual logs, some of which are as long as the dimensions of the entire accumulation. Past investigations have not examined accretion to the underside of a raft and crushing of the raft, which account for nearly all the vertical thickness of the accumulation. The recommended method for calculating the depth of drift-related local scour at pier noses depends on the estimate of an equivalent pier width. Estimation of equivalent pier widths would benefit from field data on scour depths associated with drift accumulations.

Further field investigations could lead to the definition of channel types in which drift delivery is negligible. In channels where the branches of fallen trees drag on the bed, the minimum water velocity necessary for drift transport has not yet been established. Some channels may be so shallow that practically no drift is transported. In other channels, flow deep enough to transport drift also inundates wooded flood plains, and most flood flow moves through the woods rather than along the channel. Such channels may be incapable of transporting much drift further than the woods on the neck of the next meander bend downstream.

The maximum sturdy-log length controls the potential for span blockage in wide channels. The relation between this length and regional riparian-forest characteristics has not been firmly established. Field studies of drift length and forest characteristics could refine regional estimates of the maximum sturdy-log length.

Some spans shorter than the design log length may have low potential for drift accumulation. Further research may identify bridge design features that promote transport of all floating drift through the bridge, allowing the use of shorter span lengths without incurring high potential for drift accumulation.

Many rivers transport abundant drift in every period of high water, which can create chronic drift-accumulation problems. Maintenance engineers typically know which rivers present drift problems. Assessment of the potential for drift problems should take place early in the project planning process, and communication between maintenance engineers and design engineers should continue throughout this process. Designers can then select design features appropriate for drift-prone streams at the outset of a project. Such features include adequate freeboard, long spans, solid piers, round (rather than square) pier noses, and pier placement away from the path of drift.

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