12-1999

Floating debris as a design and analysis factor for bridges and culverts

Thomas Gerald Mihlbachler

Recommended Citation

Mihlbachler, Thomas Gerald, "Floating debris as a design and analysis factor for bridges and culverts. " Master's Thesis, University of Tennessee, 1999.
https://trace.tennessee.edu/utk_gradthes/9914

To the Graduate Council:

I am submitting herewith a thesis written by Thomas Gerald Mihlbachler entitled "Floating debris as a design and analysis factor for bridges and culverts." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.

Bruce A. Tschantz, Major Professor

We have read this thesis and recommend its acceptance:

Bill Miller, Jim Smoot

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by Thomas Gerald Mihlbachler entitled "Floating Debris as a Design and Analysis Factor for Bridges and Culverts." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.

Bruce A. Tschantz, Major Professor

We have read this thesis and
recommend its acceptance:

William A. Miller Jr.

Accepted for the Council:

Associate Vice Chancellor and
Dean of The Graduate School

Floating Debris as a Design and Analysis Factor for Bridges and Culverts

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Thomas Gerald Mihlbachler
December 1999

Dedication

This thesis is dedicated to Lucas.

May your fascination with the world and beyond

never cease.

Acknowledgements

I wish to express my gratitude to Bruce Tschantz for acting as my advisor and guiding me through the past two years, Jim Smoot for providing insightful questions, Bill Miller for relating many interesting anecdotes, and Robert Houghtalen for inspiring me to pursue Water Resources. You are each a credit to the teaching profession.

I also acknowledge the contributions and moral support from my colleagues at Ogden Environmental and Energy Services, especially Mary Halley and Edwin Watkins. Your encouragement has kept me from spending the rest of eternity in Graduate School.

Foremost, however, I am indebted to my family. Your loving support, despite my many hours of absence, is a gift that I receive with the warmest of hearts.

Abstract

Over the past ten years, the scientific community has focused a significant amount of attention on the accumulation and effects of floating debris at bridges and culverts. Two bridges failed catastrophically due to floating debris during the Upper Mississippi flooding of 1993 (Parola, et al, 1994). Various professional groups recognize the importance of Large Woody Debris (LWD), the primary component of floating debris, in riverine networks, yet no solid methodology exists for the quantification of floating debris and its hydraulic effects.

This thesis aims to investigate the extent and hydraulic effects of floating debris at bridges and culverts throughout the United States, summarize the procedures for quantifying floating debris in rivers, and make recommendations for the establishment of a protocol for incorporating floating debris into the design and analysis process of bridges and culverts. State bridge engineering representatives were recently surveyed to determine opinions and data on drift-related problems, maintenance programs, and economic factors.

Literature indicates three major steps are common in the analysis of floating debris: 1) evaluation of the potential quantity of floating debris delivered to the bridge or culvert site, 2) approximation of the quantity of floating debris accumulating at the site, and 3) hydraulic representation of the site incorporating the potential floating debris

accumulation. The methods and models reviewed were the Diehl (1997) qualitative method of potential drift accumulation, the Debris at Bridge Pier Prediction Program (DBP3) (Wallerstein, 1999) for both quantification of potential drift accumulations and scour, and HEC-RAS (U.S. Army Corps of Engineers, 1998) for quantitative hydraulic values.

A common opinion of state bridge engineers was formed from the survey results, indicating that the most efficient way to approach floating debris accumulations at bridges and culverts is to operate on a case-by-case basis at the local level. This approach, however, has led to a general failure to observe the costs associated with floating debris removal, repair of damages, and maintenance.

The adoption of a consistent protocol for the quantification of floating debris accumulations has been hampered by the many site dependent variables associated with floating debris accumulations and their hydraulic effects at bridges and culverts, but one should be undertaken in order to guide engineers and modelers in the consideration of drift in the design and analysis process of hydraulic structures. An analysis protocol considering both qualitative and quantitative factors is presented to evaluate the potential hydraulic effects of floating debris, implementing flowcharts and computer models to guide the process.

Preface

Research into the field of floating debris accumulations at bridges and culverts is confounded by a lack of consensus regarding terminology. Throughout this thesis, the terms "floating debris" and "drift" may be used interchangeably, each referring to objects transported at or near the surface of the water. The general term "debris", however, is often associated with the transport of rock or other sediment-water mixtures in the context of debris torrents (Perham, 1987) and should be avoided in the context of floating debris in order to prevent confusion. The term "debris", however, is abundant in literature and may be used occasionally when citing works. The general term "trash" typically refers only to man-made litter, which comprises a small percentage of the floating debris experienced in most non-urban watersheds.

Table of Contents

List of Figures

Figure **Page**

List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AHTD	Arkansas State Highway and Transportation Department
CEM	Channel Evolution Model
CPOM	Coarse Particulate Organic Matter
DBP3	Debris at Bridge Pier Prediction Program
DOM	Dissolved Organic Matter
FHWA	Federal Highway Administration
FPOM	Fine Particulate Organic Matter
HEC-RAS	USACE Hydrologic Engineering Center – River Analysis System
LWD	Large Woody Debris
LRFD	Load and Resistance Factor Design
NCHRP	National Cooperative Highway Research Program
PennDOT	Pennsylvania Department of Transportation
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
WSDOT	Washington State Department of Transportation

List of Symbols

A	flow cross-sectional area normal to the direction of the flow
A_D	area of floating debris accumulation
B	blockage ratio
C	depth to the center of the moment of pressure
C_D	drag coefficient
d	diameter of LWD
D	pier diameter
D_d	width of floating debris accumulation
D_e	effective pier diameter
f	Darcy-Weisbach friction factor
F	width – depth ratio in channel
$\mathbf{F}$	Froude number
F_D	dynamic force of flowing water
F_p	hydrostatic force
g	acceleration due to gravity
h_1	water depth upstream of floating debris accumulation
h3	water depth downstream of floating debris accumulation
Δh	backwater afflux due to LWD
H_T	stable tree trunk height
L_D	length of debris accumulation in the direction of flow
n	Manning's roughness coefficient
Q	flow rate
Q_b	bankfull discharge
R	hydraulic radius
S	energy slope
S_o	channel bed slope
T_d	depth of floating debris accumulation
T_d*	effective length of floating debris raft
V	mean flow velocity
V_1	mean velocity at the section upstream of the floating debris accumulation
V_3	mean velocity at the section downstream of floating debris accumulation
w	average channel bottom width
W	channel width
y	flow depth
ρ_w	density of water
ω	specific stream power
γ	specific weight of water

I. Introduction of Issues and Concerns

Over the past ten years, the scientific community has focused a significant amount of attention on the accumulation and effects of floating debris at bridges and culverts. Two bridges failed catastrophically due to floating debris during the Upper Mississippi flooding of 1993 (Parola and others, 1994). Various professional groups recognize the importance of floating debris in riverine networks. State and county bridge maintenance departments are well aware of the potential for floating debris blockages, resulting in decreased capacity and increased lateral forces and backwater effects. Hydropower companies are concerned with the effects of floating debris at their dams (Swann, 1999). Geologists recognize the accumulation of Large Woody Debris (LWD) as a significant factor in the creation of valley plugs and the geomorphic characteristic of a riverine system (Diehl, 1994). Ecologists have found that LWD, which compromises an estimated ninety percent of floating debris accumulation volume, plays a significant and positive role in riverine ecosystems by enhancing aquatic habitat (Smith and Collopy, 1998). Typical design specifications mandate an allowance for debris rafts or blockage when designing a bridge or culvert, both hydraulically and for scour potential (Burns, 1999). Yet, amid this focus, no consistent methodology for quantifying the accumulation of floating debris and its hydraulic effects at bridges and culverts has become widely accepted.

Background

Floating debris can be an integral part of the behavior of a riverine system, especially during high flow conditions. Floating debris typically acts as an obstruction to the flow, reducing capacity of many structures and channels. Accumulations of floating debris, typically referred to as debris jams within a channel or debris rafts near a hydraulic structure, alter the flow paths, concentrate velocities and increase the likelihood of scour during extreme events. Hamilton and others (1994) stress that "the presence of sediment or debris [during extreme floods] may drastically impact the characteristics of the receiving area thus blocking off preferential flow paths and flooding areas that may have been previously considered safe".

After a storm event, floating debris is often deposited throughout the channel reach and in its floodplains as debris accumulations. An example of such a debris deposition at a bridge pier is shown in Figure 1. Cleaning or "snagging" the channel of deposited debris after a storm event has been common practice for reducing the effects of floating debris, but this practice has recently come under fire for causing adverse ecological and sediment transport impacts within the riverine system (Gurnell, 1997). Smith and Collopy (1998) states, "removal of woody debris from streams … reduces the supply of food and stable substrates for benthic organisms and reduces retention of the detritus that other

Figure 1. Woody debris accumulation at a bridge pier along the New River Trail in southwest Virginia. (Photo courtesy of Tschantz)

invertebrates eat." Fish and other higher species use deposited debris accumulations for feeding, breeding, and protection from predators (Wallerstein and others, 1996a).

Hydraulic engineers have found themselves needing to reevaluate their approach to quantifying and mitigating the effects of floating debris. In most cases, floating debris is assessed on a case-by-case basis and lacks an evaluation protocol. Quotes Rebecca Burns of the Pennsylvania Department of Transportation Bureau of Bridge Design "[The American Association of State Highway and Transportation Officials] AASHTO design specs (both Standard Specs 3.18.1.3 and [Load and Resistance Factor Design] LRFD

Specs 3.7.3.1) include a broad direction to consider debris or drift loading, but no solid methodology" (Burns, 1999).

Section 3.18.1.3 of the AASHTO Standard Specifications for Highway Bridges (1997) states, "Where a significant amount of drift lodged against a pier is anticipated, the effects of this drift buildup shall be considered in the design of the bridge opening and the bridge components. The overall dimensions of the drift buildup shall reflect the selected pier locations, site conditions, and known drift supply upstream. When it is anticipated that the flow area will be significantly blocked by drift buildup, increases in high water elevations, stream velocities, stream flow pressures, and the potential increases in scour depths shall be investigated." Unfortunately, the AASHTO Standard Specifications give no further guidance on assessing or including the hydraulic effects of floating debris on design.

The AASHTO LRFD Bridge Design Specifications (1998) comments, in section C3.7.3.1, "Floating logs, roots, and other debris may accumulate at piers and, by blocking parts of the waterway, increase stream pressure load on the pier. Such accumulation is a function of the availability of such debris and level of maintenance efforts by which it is removed. It may be accounted for by the judicious increase in both the exposed surface and velocity of water." The commentary also adopts provisions for the estimation of drift volume and the associated increased stream pressure at bridges from the New Zealand

Highway Bridge Design Specifications. These provisions shall be addressed later in this thesis, in the Drift Accumulation at Bridges and Culverts section of the Literature Search.

Objective

Drift accumulation can be a significant and quantifiable factor in river and stream hydraulics, and should be a major consideration in the planning, design and analysis process of culverts and bridges. This thesis aims to (1) investigate the extent and hydraulic effects of floating debris at bridges and culverts throughout the United States, (2) summarize the procedures for quantifying floating debris in rivers, (3) make recommendations for the establishment of a methodology for incorporating floating debris into the analysis process of bridges and culverts, and (4) obtain opinions and data on drift-related problems, maintenance programs, and economic factors from state bridge engineering representatives.

Scope

This thesis will explore and summarize the current knowledge and design philosophy regarding floating debris in riverine systems. Non-floating debris will be addressed in the context of a common fate of drift, but shall generally be considered outside the focus and scope of this research. Effects of floating debris in large bodies of water (i.e., in reservoirs, lakes, and oceans), at dams and their inlet or outlet works, and at navigational locks shall be considered outside the scope of this thesis. For the purposes of this thesis, ice shall be considered a separate entity from floating debris and, thus, also be outside of the scope. An in-depth literature review of design documents, analysis guides and other related publications will be summarized. Recommendations for the establishment of a floating debris quantification protocol shall be presented. The opinions of state bridge engineering representatives and data on drift-related problems, maintenance programs, and economic factors shall be evaluated through a recent survey questionnaire. A discussion for estimating quantities of drift using the Debris at Bridge Pier Prediction Program (DBP3) (Wallerstein, 1999) and hydraulic effects using the US Army Corps of Engineers (USACE) Hydrologic Engineering Center's – River Analysis System (HEC-RAS) (US Army Corps of Engineers, 1998) shall be presented. Both cost and scour, with respect to floating debris accumulations, are extremely important and will be briefly addressed as consideration factors. Generally, however, the inherent complexities associated with floating debris scour and costs make these topics impractical to adequately address in this thesis.

II. Literature Review

A significant amount of literature is available on the topic of floating debris, which has been given increased attention over the past ten years due primarily to its multidisciplinary nature, as indicated in the introduction of this thesis. Literature sources were gathered primarily through various database collections: the EI Compendex Plus, Water Resources Abstracts, National Technical Information Service, Transportation Research Information Services, and the Web of Science Citation database. An Internet search yielded contributions from the United States Geological Survey (USGS), most notably a recent report on potential drift accumulation (Diehl, 1997).

The majority of the literature has centered on four broad categories: (1) drift characteristics, (2) effects of floating debris on the riverine system, (3) the hydraulic effects of drift accumulation at bridges and culverts, and (4) the prevention, control and mitigation of floating debris. Drift characteristics topics include drift constituents and distribution, generation processes, and transport phenomenon. Topics regarding the effects of floating debris in riverine systems typically revolve around the effects of deposited Large Woody Debris (LWD) and include increased frictional losses in the channel, the geomorphologic character of the river, ecological habitat concerns, and sediment transport capability. The hydraulic effects of floating debris accumulation at bridges and culverts typically involve blockage and scour potential concerns. Prevention, control and mitigation topics include trash awareness programs, general design considerations, deflection and interception techniques, and the complexities associated with proper maintenance.

Several cases of bridge damage or failures exist in which drift accumulation is documented as a significant factor. Chang (1973) estimates that twenty percent of the reported cases of damage to a bridge, during the major floods of the years 1969-1972, resulted from floating debris. Parola and others (1994) reports that both a Missouri Highway 113 bridge near Skidmore, Missouri, and a county bridge over Halfbreed Creek in Richardson County, Nebraska, failed catastrophically due to hydrodynamic forces imposed by floating debris during the Upper Mississippi flooding of 1993. The National Transportation Safety Board (1990) reported a large drift accumulation striking a highway bridge immediately before failure occurred in Miamitown, Ohio. Diehl (1997) indicates that "many other [failures due to] drift accumulation have been reported in engineering literature, but few reports contain much detail about drift itself." Due to safety concerns, very few accounts involve first-hand accounts of damage to bridges or culverts, and, thus, most damage studies are retrospective in nature. Detailed scour and hydraulic measurements are possible, however, and were made around a floating debris accumulation at a bridge over the Brazos River near Lake Jackson, Texas, during a flood event (Mueller and Parola, 1998), illustrating the very complex and non-uniform nature of the hydraulic situation near drift accumulations.

Drift Characteristics

Floating debris compositions are typically estimated to contain approximately ninety percent LWD by volume, such as at the Huntsville Spring Branch floating debris removal project (Sadler, 1999). Drift can vary significantly, however, depending on the characteristics of the watershed. For instance, McFadden and Stallion (1976) report that ninety-nine percent of the floating debris, by volume, on the Chena River in Alaska is woody, while Carleton and Nielsen (1990) indicate that urban floating debris is compromised primarily of yard refuse, plastic objects, and paper objects. This variation highlights the difference between urban and rural floating debris compositions, whereas urban floating debris typically has a higher percentage of trash and less LWD. At root of this variance are the land use practices present in the contributing watershed, especially in the case of improper forestry practices (i.e., clear cutting) (Perham, 1988) (Diehl, 1997) which more frequently tend to deliver large, stable woody debris. The composition of floating debris greatly influenced the design procedure at the Clover Fork Diversion Tunnel Project near Harlan, Kentucky, where the potential floating debris includes unstable housing (trailer homes), stockpiles of logs, and trees (Martin, 1989).

Since LWD composes the majority of floating debris, LWD characteristics will dominate the behavior of floating debris. Diehl and Bryan (1993) report that "tree trunks with attached root masses were the dominant type of long debris, and limbs and trunks separated from the stump by breaking or cutting were the dominant type of shorter debris."

Diehl (1997) develops the principle of the design log length to be used in characterizing floating debris accumulations at bridges. The design log length represents the maximum sturdy length of logs to be delivered to a specific site and is the smallest of the following values:

- the width of the channel upstream from the site,
- the regional maximum sturdy length of logs, or
- nine meters plus one-quarter of the upstream channel width.

For narrow channels, logs longer than the width of the upstream channel cannot be transported until they have been reduced to a length that will fit into the channel. Large channels can transport the entire log and, thus, the regional maximum sturdy log length could be an observed value or estimated from the height and diameter of mature trees in that region. The third value is empirically based on observed drift accumulations in intermediate channels (12m – 60m) throughout the United States.

Generation

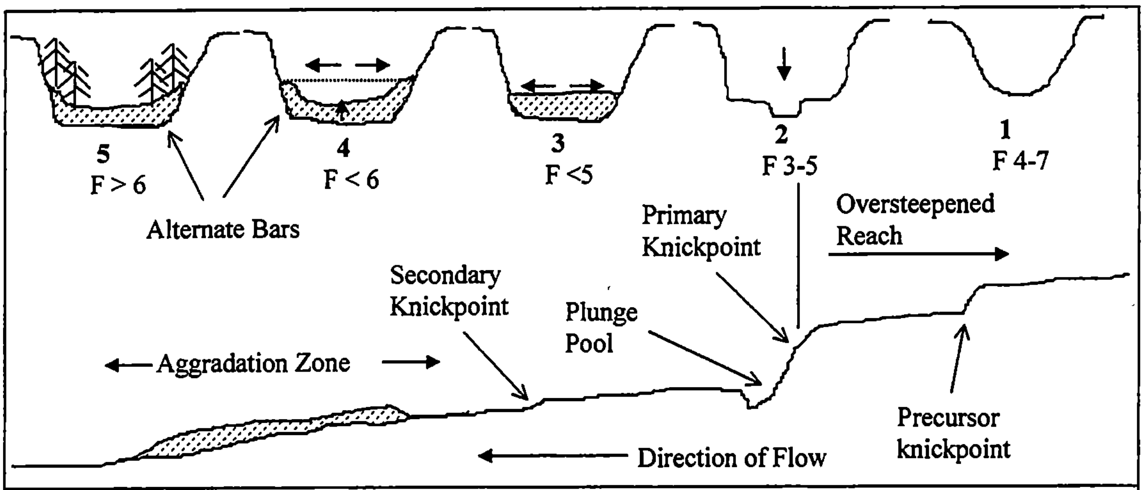
Most drift is generated by trees growing on or near the banks or bank tops of a channel (Diehl, 1997). Perham (1988) identifies erosion as the primary method by which floating debris is introduced into a channel, through the process of general outer bank erosion (caused by the tractive force exerted by the water) or through mass wasting (caused by channel instability). Asymmetric root masses, a common characteristic of LWD, and the presence of bark on trunks are indications that trees enter the stream alive, undermined by fluvial erosion, and are then detached from the bank (Diehl and Bryan, 1993). Other input mechanisms include trees felled by windstorms, ice storms, and landslides in steep regions, forest litter, and beaver dams. These input mechanisms would vary in magnitude depending on watershed characteristics. Perham (1988) also notes that agricultural and construction materials sometimes become a component of floating debris, noting " the most troublesome of these perhaps is the plastic film or sheets that eventually become draped over trash racks and screens." Improper forestry practices may also contribute significantly to the quantity of floating debris, especially in clear-cut areas (Perham, 1988). Diehl (1997), however, indicates that improved forestry practices have reduced the amount of floating debris input generated by the timber industry. The incidence of drift generation may be chronic or episodic, where chronic inputs (bank failure and tree mortality) are frequent but produce a small amount of material, and sporadic inputs (such as wind throw, ice storms, etc.) are infrequent but large in magnitude (Wallerstein and others, 1996a).

Some aspects of drift generation are not necessarily inherent, especially the estimation of drift volume. Wallerstein and others (1999) have found that unit stream power has a positive correlation to floating debris volume in a study performed of the unstable rivers of northern Mississippi. Specific stream power is defined as:

$$\omega = \frac{Q_b S \rho_w g}{w} \tag{1}$$

where: ω = specific stream power (Watt/m^2); Q_b = discharge at full bank conditions (m^3/s); S = channel bedslope (m/m); ρ_w = density of water (kg/m^3); g = gravitational constant (m/s^2); w = average channel bottom width (m). The statistical correlation indicates that as stream power increases, the volume of drift transported to a site will also increase. Yet the study yielded no statistically significant relationship between drainage basin area and floating debris volume, strengthening the argument that debris volume may be spatially varied and more reliant on factors such as channel sinuosity and reach stability (Wallerstein and others, 1999). Three methods for estimating potential volumes of drift at bridges are further discussed later in this Literature Search, in the Drift Accumulation at Bridges and Culverts section.

Wallerstein and others (1999) evaluated floating debris input by channel reach versus the Channel Evolution Model (CEM) to place drift generation in the context of the channel evolutionary process. In the CEM, five stages of channel evolution are presented, ranging from a stable stream, through vertical and lateral degradation, to aggradation and a return to channel stability. The CEM is shown in Figure 2. Floating debris input rates were found to correspond accordingly. Stage 1 and 5 channels, which are stable and have low erosion, have low volumes of drift. Stages 2 and 4, characterized by local bank



Schematic cross sections corresponding to reaches on the long profile show the evolution of the reaches from Type 1 to Type 5. Typical width-depth (F) values are shown. Size of arrows indicate the relative importance and direction of dominant processes

Figure 2. Longitudinal profile of an active channel showing features of the Channel Evolutionary Model (CEM). (from Wallerstein, et al. 1999)

erosion, have significantly higher floating debris input, while Stage 3, with rapid lateral erosion of the banks, produces the greatest volumes of drift. The CEM can therefore offer relative magnitudes of floating debris production in channels that are evolving (Wallerstein and others, 1999).

A high degree of correlation between erosion and drift generation leads Wallerstein and others (1999) to conclude, “debris input can therefore be predicted to occur where the channel is undergoing degradation or is actively meandering.” Diehl and Bryan (1993) agree that “high and steep banks, erodible bank materials, and a history of channel widening or lateral migration all are useful as indicators of potential bank erosion and consequent debris production”, and further suggest the use of aerial photography and maps in the detection of channel widening or lateral migration.

Transport

Large quantities of floating debris are most often associated with storm events, due to their input processes, and thus high flow conditions are typical of the transport situation. The size of the channel greatly influences the transport phenomenon associated with floating debris. In narrow channels where the LWD is longer or equal to the channel width, trees will tend to span the channel and become a debris jam. The debris jam will typically gather smaller debris until it is either removed by a large flood, or decomposes (Perham, 1988). Drift accumulations have been observed at bridges with upstream channels as narrow as 3 to 4 meters (Diehl, 1997).

In intermediate and large channels, where the channel width is greater than the LWD length, floating debris is transported at the water surface or perhaps suspended at some distance beneath it (Perham, 1987). Drift transported below the water surface, especially during flood situations, is hard to observe and evaluate; thus the abundance and effect of submerged drift can only be inferred (Diehl, 1997). Diehl (1997) also indicates drift will tend to follow the talweg of the channel, a zone of convergence where the flow is deepest and the velocities are typically the highest, and thus will be transported at the average water velocity. Wallerstein (1999) notes that individual trees will tend to travel alone and to align themselves in the direction of flow, with either the canopy or root mass directed downstream (whichever is heavier and larger). Diehl (1997) asserts that other floating debris will commonly group into short-lived clumps that travel downstream until they are broken apart by turbulence or a collision with a stationary object.

During extreme flood events, when the flood plain inundation exceeds roughly one-third channel depth, the zone of convergence in the channel dissipates and the flow path follows the natural contours of the valley. In this situation, it has been found that wooded floodplains will block the transport of drift, and possibly remove more floating debris than is introduced by the floodplain (Diehl, 1997).

Floating Debris Effects on the Riverine System

The impacts of floating debris on the riverine system largely revolve around the effects of floating debris after it has accumulated. Topics of concern regarding the effects of floating debris include aesthetic perceptions, safety issues, navigation, ecological habitat concerns, increased frictional losses in the channel, the geomorphologic character of the river, and sediment transport capability.

Trash depositions improperly located in valleys or along water bodies become sources of floating debris during surface runoff or flooding events. Although trash and other man-made materials make up only an estimated 10% of floating debris (Sadler, 1999), the aesthetic detriment caused by its distribution can be profound. The Huntsville Spring

Branch drains the urban watershed of Huntsville, Alabama and surrounding Madison County, and deposits floating debris into the Redstone Arsenal and the Wheeler Wildlife Refuge and reservoir. According to Sadler (1999) "the deposits detract from the natural aesthetics, adversely affect river hydraulics, increasing flooding, and destroy wildlife." Aesthetics is typically a difficult parameter to quantify, but it receives considerable attention from the general public.

Floating debris can be a significant factor in the safe operation of both commercial and recreational boats on riverine systems. B. Schmidt from the U.S. Coast Guard Office of Boating Safety (*in* Swann, 1999) reports "of the over 800 recreational boating-related deaths in 1997, 13 are directly attributed to collisions with floating objects other than boats or vessels...[and] the number of accidents caused by collisions with floating objects is rising." Commercial boats can also have accidents when floating debris is present at navigation locks (Swann, 1999).

After a storm event, floating debris is often deposited throughout the channel reach as debris accumulations, which provide substrate for much of the invertebrate species and higher species (Shields and Gippel, 1995). Wallerstein and others (1996a), assert that the deposited LWD provides substrate through a process of retaining and decomposing Coarse Particulate Organic Matter (CPOM) into Fine Particulate Organic Matter (FPOM) and Dissolved Organic Matter (DOM). The pools and riffle sequences created by LWD also help to oxygenate the flow, thus improving the aquatic habitat. Fish and other higher species use deposited debris accumulations for feeding, breeding, and protection from predators. The researchers indicate that the importance of LWD in the stream environment is apparent when considering that stream restoration programs that aim to enhance aquatic habitat introduce LWD or simulated materials into streams.

Increased Roughness

As the deposition of floating debris greatly influences the aquatic habitat, it also contributes to the dissipation of stream energy. Several authors including Abt and others (1998), Shields and Gippel (1995), Diehl (1997) have noted the effect of LWD on flow resistance. Abt and others (1998) stress the importance of roughness due to debris deposits, "Normally, the effect of debris is not considered by the engineer when determining the resistance to flow, i.e., Manning's n, for a specified reach. Therefore, channel capacity and/or slow conveyance are often poorly estimated," (i.e., the capacity is typically overestimated when ignoring deposited debris).

A primary equation used widely by river engineers to calculate uniform flow discharges or determine roughness coefficients is the empirically based Manning's equation:

$$Q = \frac{1.486}{n} A R^{\frac{2}{3}} S^{\frac{1}{2}} \tag{2}$$

where: Q = flow rate (ft^3/s); n = roughness coefficient; A = flow cross-sectional area normal to the direction of the flow (ft^2); R = hydraulic radius (ft); S = energy slope (ft/ft);

and 1.486 is the conversion to U.S. customary units. Manning's "n" values are typically estimated though descriptive tables in Chow (1959) or from photographs with descriptive details in Barnes (1967). Wallerstein (1996a) reports that Manning's "n" values, which are typically in the range 0.025 - 0.15, may exceed 1 in small stream where the obstruction caused by LWD is great with respect to the flow depth, and thus invalidate the Manning's equation. As with most boundary friction factors, the effects of LWD on flow resistance decrease as the flow depth increases.

Experiments have estimated the frictional losses due primarily to LWD by first determining a roughness coefficient for a reach that contains LWD, and then removing the debris and measuring the roughness coefficient at a similar flow depth (Abt and others, 1998)(Shields and Gippel, 1995). Both experiments indicate that deposited debris increases the roughness coefficients of a stream, but different friction factors were measured. Abt and others (1998) report an average increase in Manning's n values of 39% attributed to the presence of woody debris. Shields and Gippel (1995), on the other hand, adopted the Darcy-Weisbach equation and found that friction factors increased only 20-30%, relating to an increase in bankful capacity of 5-20%. The Darcy-Weisbach equation, also for non-uniform flow, is:

$$V = \sqrt{\frac{8gRS}{f}} \tag{3}$$

where: V = mean flow velocity (ft/s); R = hydraulics radius (ft); S = energy slope (ft/ft) ≅ S_o = channel bed slope (ft/ft); g = gravitational constant (ft/s^2); and f = Darcy-Weisbach friction factor. Comparing equation (2) and (3), we can relate the Darcy-Weisbach friction to Manning's n (Tschantz, 1999):

$$n = 0.09284 f^{\frac{1}{2}} R^{\frac{1}{6}} \tag{4}$$

Thus, a 20-30% increase in the Darcy-Weisbach friction factor as witnessed by Shields and Gippel (1995) equates to a 10-15% increase in Manning's n. The trend that deposited drift increases the roughness characteristics of a channel are apparent, but the magnitude of that increase is still unclear.

One major obstacle in the determination of accurate friction losses for LWD deposits is spatial variation of the obstruction along the reach. Wallerstein and others (1999) found no statistical correlation between the average number of jams (jam frequency) and drainage basin area or unit stream power, stating "the use of hydraulic geometry and energy relationships to predict the distribution of debris is therefore too simple an approach to understanding debris dynamics in these unstable channel environments." Channel sinuosity and reach stability are recommended as being better indicators of jam frequency.

Channel Morphology

The deposition of floating debris acts as a significant factor in the average condition and variance of channel dimensions, magnitude and distribution of pools and riffles, and the overall stability and pattern of river channels (Gurnell, 1997). These factors apply to both the local channel scale and the reach scale.

Wallerstein et al (1996a) indicate that local effects of floating debris include increased local scour and variations in flow distribution. Concentrated velocities around drift accumulations incur both local bed and stream bank erosion. Drift accumulations within a channel may cause one of four debris jam types depending upon the stable tree trunk height (H_T) (i.e., that part of the tree resistant to being broken apart) to channel width (W) ratio:

1. Underflow jams – [$W < H_T$] in lower order streams where fallen trees span the entire channel at the top of bank. Local bed erosion may occur during high flows; otherwise the effects of this type of jam are minimal.
2. Dam jams – [$W \cong H_T$] occur where drift spans the entire cross-section, causing significant local bank erosion and bed scour due to concentrated flows. Backwater effects may cause deposition of sediment upstream and bars may form immediately downstream.
3. Deflector jams – [$W > H_T$] form where the drift does not span the entire channel, and thus the flow is directed towards the opposite bank causing localized rapid bank erosion and bed scour. Significant bank erosion may lead to the introduction of more drift into the channel. May cause upstream

sediment wedges and sand bars downstream if bed load and suspended sediment transport not possible.

4. Flow parallel jams – [$W >> H_T$] occur in higher order channels where the drift rotates so as to become parallel to the flow. Drift will then be transported downstream and accumulate along the banks, in meander bends, or at man-made structures. These types of drift jams may actually prevent bank erosion by armoring the bank toes.

Gurnell (1997) states that LWD dissipation of stream energy directly leads to influences on the distribution of overbank flows, which results "in the cutting of new channels and the abandonment of old ones."

Diehl (1994) reports that drift accumulations in the low-gradient alluvial streams in West-Tennessee are a primary cause of the valley plug phenomenon. In lower order streams, drift deposits block the channel, decreasing flow capacity and thus also reducing velocity. The sediment transport capability of the channel is reduced, channel aggradation ensues and the combination of sediment and drift accumulation forms the valley plug. As a result, flow shifts into an alternative channel(s) and may induce degradation of the downstream reach, and thus more drift generation.

Wallerstein et al (1996a) continues that reach characteristics are most significantly influenced by drift accumulations through the creation of pools and riffles, which have been shown to be positively related to the distribution and volume of drift in channels. The dual nature of floating debris generation, both chronic and sporadic, distorts the pool and riffle sequence so that it has very little spatial memory or periodicity.

Sediment Transport

Drift accumulations affect the sediment transport capacity of the riverine system with a dual-role function (Wallerstein and others, 1999). Sediment transport is reduced by drift jams through lowered velocities in the associated backwater reaches, but local scour and erosion caused by the concentrated flows around floating debris accumulations increase the suspended load. Wallerstein and others (1996a) use four classes of drift jams to describe their roles in sediment transport: (1) underflow jams interfere very little with the flow path, since the drift is typically suspended above the main channel, and thus they have very little associated sediment retention and scour characteristics, (2) dam jams have a pool associated with the jam, and thus store large volumes of sediment in backwaters, but they also incur plunge pool scour, (3) deflector jams produce bar deposits upstream near the jam, but then causes significant bank erosion, and perhaps bank failure, as it causes the flow to impinge into one or both of the banks, and (4) flow parallel jams do not alter the flow path significantly, as they are typically situated on the banks in the direction of flow, and thus they do not affect the channel's sediment retention and scour characteristics. Flow parallel jams may, however, act to reduce sediment loading by armoring the channel banks.

During a study of sand and gravel bed rivers in the Yazoo Basin in northern Mississippi, Wallerstein and others (1999) performed a sediment budget in each reach. No statistical relation, either positive or negative, was found relating the sediment budget to drainage basin area, which indicates that no spatial trends relate these variables. Thus, the drainage area cannot characterize the effect of debris jams on sediment transport. The sediment budgets do show, however, that "the balance between sediment scour and sediment retention caused by debris jams is in favor of net sedimentation."

Shields and Gippel (1995) observed various hydraulic effects of a deposited debris removal project on the Obion River in western Tennessee, and noted "visual observation of bank erosion following debris removal combined with evidence of headward-progressing degradation suggested that debris removal may have triggered or exacerbated bed lowering."

A negative feedback mechanism typifies the relationship between floating debris and sediment transport in the case of channel degradation. An increase in debris input due to channel degradation-induced bank erosion would, in turn, cause greater accumulations of debris in the channel. The debris accumulation will result in increased water surface elevation, lower velocities and, thus, allow greater sediment storage. "Channel bed elevation is consequently raised once more and the rate of bank failure and debris input is thereby reduced" (Wallerstein and others, 1996a).

Floating Debris Accumulation at Bridges and Culverts

Floating debris accumulation at a bridge on U.S. Highway 412 near Huntsville, Arkansas, caused the bridge to be closed by the Arkansas State Highway and Transportation Department (AHTD) to repair damage. "The damage occurred when a fallen tree lodged under the bridge causing water to be diverted outside the normal creek channel. The water undermined the roadway at one end of the bridge and caused a portion of the bridge end support to become unstable" (Arkansas State Highway and Transportation Department, 1999).

The hydraulic effects of floating debris accumulation at bridges and culverts typically involve blockage and scour potential concerns. Wallerstein (1999) lists four possible consequences of floating debris blockages: backwater effects, local flow diversion, channel erosion, and structural failure. Due to the inherent hydraulic differences between bridges and culverts, the hydraulic effects of floating debris accumulations at bridges and culverts vary, and thus, need to be treated separately.

The size of the floating debris accumulation greatly influences the hydraulic effects at a bridge. A drift accumulation will reduce the flow capacity through the bridge opening, thus concentrating flow velocities and increasing the likelihood of scour (Melville and Dongol, 1992) (Diehl, 1997) (Wallerstein, 1999), will raise backwater levels upstream from the bridge (Wallerstein, 1996a), and will also translate an increased amount of hydrostatic (Wallerstein, 1999) and dynamic stream forces to the bridge substructure (AASHTO, 1998). A primary factor in determining the extent of these effects is the estimation of the quantity of drift arriving at a site.

Three recent methods for estimating the volume of drift arriving at a site are apparent in literature. Diehl (1997) approximates the size of potential debris arriving at a site based upon the qualitative risk category of the structure and the total potential drift input upstream of the site. AASHTO LRFD (1998) estimates the size of a drift accumulation based upon either site dimensions or a standard value. Wallerstein (1999), on the other hand, adopts a statistical approach towards determining the amount of total potential floating debris trapped at a structure.

Diehl (1997) studied LWD accumulations at various bridges throughout the United States, and divided drift accumulations into two main classes: single pier accumulations and span blockages. Single pier accumulations were observed to have primary full-width logs that supported smaller debris, and were typically less than 50 ft wide. In some locations with upstream bar aggradation, it was observed that island development promoted unusually wide single pier accumulations. Span blockage occurs when the size if the stable drift length (H_T) is greater than the minimum bridge clear span (L_S), in which case a log may span from one pier to another, or to any obstruction in the channel or on the bank. Again, full-width logs were observed by Diehl to support smaller debris in this type of drift accumulation. Observed span blockages were primarily less than 60 ft wide, but were found to be greatly dependent on the width of the clear span. Most observed drift accumulations were similar in shape, being narrow at the base and becoming wide at the water surface. The greatest depths of drift accumulations are located at piers, being controlled by the depth of flow. Some drift accumulations have been observed to extend to the channel bed during extreme storm events.

With the observation that long logs hold provide the primary structure of floating debris accumulations, Diehl (1997) implements the idea of design log length and site characteristics in representing the size and shape of potential drift accumulations. The concept of design log length is discussed in the Drift Characteristics section of the Literature Search. Diehl divides the assessment of potential drift accumulation into three major qualitative phases, each with subordinate tasks, as shown in Table 1.

The first major phase is the estimation of the total potential drift delivery. This phase is comprised by the tasks of estimating the potential for the river to deliver drift to the site, estimating the size of the largest drift, and classifying the bridge components into location categories. The task of estimating the river's capability to deliver drift is based upon direct observations of drift, indirect evidence of drift generation (i.e., widespread upstream bank erosion, etc.), or indirect evidence of drift transport (i.e., channel ability to deliver drift). A flow chart for this task is shown in Figure B1, in Appendix B of this thesis. Determining the design log length (as discussed in the Drift Characteristics

Table 1. Major phases and tasks in evaluating potential for drift accumulation at a bridge. (from Diehl, 1997)

Major Phase	**Tasks**
1. Estimate potential for drift delivery.	a. Estimate potential for drift delivery to the site. b. Estimate the 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.

section of the Literature Search) is the second task. As the third task, bridge components are assigned location categories to relate overall likelihood of drift interception. The location categories are (in decreasing likelihood of drift capture): drift path (talweg), channel, bank/floodplain, and sheltered (i.e., protected from drift by a forested floodplain). A flow chart for this task is shown in Figure B2, in Appendix B of this thesis. Through the qualitative observance of these three tasks, the overall potential for drift delivery to the site can be determined.

The evaluation of bridge characteristics, with respect to drift interception, is the second major phase of estimating potential drift accumulation. The primary bridge elements of concern are: piers, abutment bases, gaps between fixed components of the bridge opening, and sections of the superstructure that come in contact with the water surface.

The tasks of this phase of the evaluation are as follows: assign location categories to each bridge element, determine whether bridge elements have sufficient gaps to allow passage of the design log length, and determine whether submersed superstructure components have flow carrying apertures. Flow charts for estimating the potential for accumulation across spans or on individual piers are shown in Figures B3 and B4, respectively, in Appendix B of this thesis.

The final phase of estimating potential drift accumulation at bridges is the phase that calculates a hypothetical drift loading for the entire bridge. Diehl provides only relative terms to relate the various drift loadings: low, medium, high, and high chronic potential. The conservative assumption that the drift accumulation extends from the water surface to the channel bed, with equal width over its full depth is recommended. The width of the floating debris accumulation is to be estimated as the design log length for single pier accumulations and for span blockages, the width shall be the span width plus ½ design log length on either side of the span. The summation of each individual component's drift loading will then yield the total drift accumulation for a bridge. Obviously, Diehl intends this method of estimating the total floating debris accumulation at a bridge to be a conservative estimate.

The AASHTO LRFD specifications (1998) state "the size of the debris raft [floating debris accumulation] is a matter of judgment", but then go on to recommend that as a guide, the depth of the debris raft (T_d) illustrated in Figure 3 should be half the water

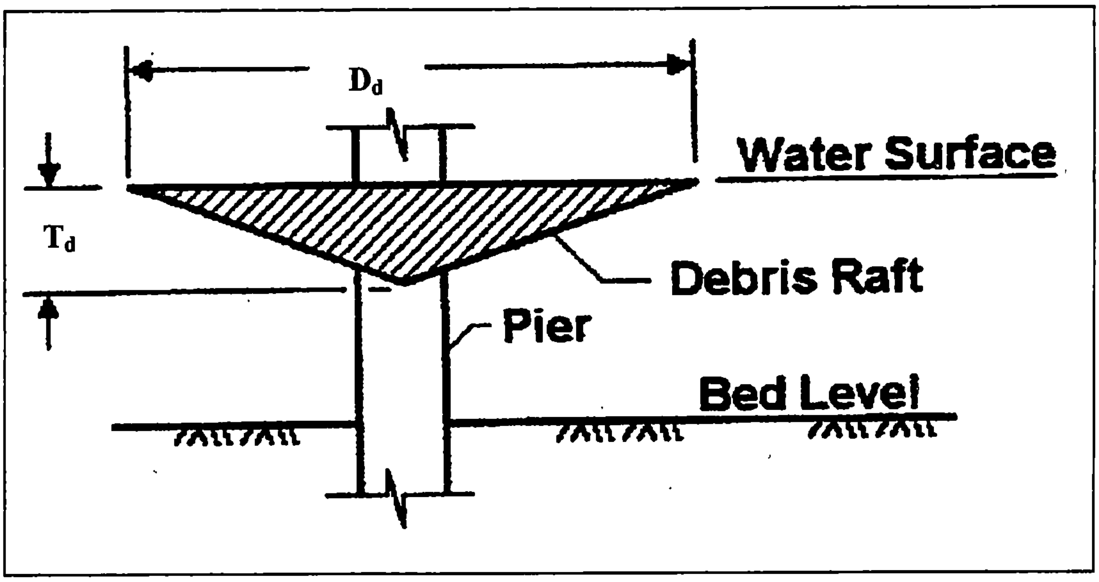


Figure 3. Floating Debris Raft Dimensions. (adapted from AASHTO, 1998)

depth, but not greater than 10 ft. The width of the debris raft (D_d) should be half the sum of adjacent span lengths, but no greater than 45 ft. This approach assumes that the drift accumulation will form in a triangular shape and will provide a conservative estimate. In some instances, however, this approach will underestimate the debris raft size, especially if span blockages occur.

Wallerstein and others (1996a) implement a probabilistic method to determine the accumulation of drift at a bridge. The probabilistic approach considers the size of the bridge opening and the respective size of the drift. The probability of each piece of drift becoming trapped is calculated, with the probability increasing correspondingly whenever a piece of drift becomes trapped, thus reducing the bridge opening. The total number of drift input is estimated in this procedure by multiplying the tree density of the upstream

upstream floodplains by the reach length by the average bank retreat width (due to erosion) by two (for there are two banks).

Melville and Dongol (1992) investigated the role that floating debris accumulations play in local bed scour at bridge piers. The principle of the effective pier diameter (D_e) is presented. The effective pier diameter is a hypothetical value that best represents the combined effects of pier scour with drift loading at the actual pier, to be used in the place of the actual pier diameter into scour equations that do not take drift loading into consideration. A descriptive illustration of the Melville and Dongol theoretical model can be seen in Figure 4. The suggested effective pier diameter can be calculated by:

$$D_e = \frac{T_d^* D_d + (y - T_d^*) D}{y} \tag{5}$$

where: D_e = effective pier diameter (ft); y = flow depth (ft); D = pier diameter (ft); and

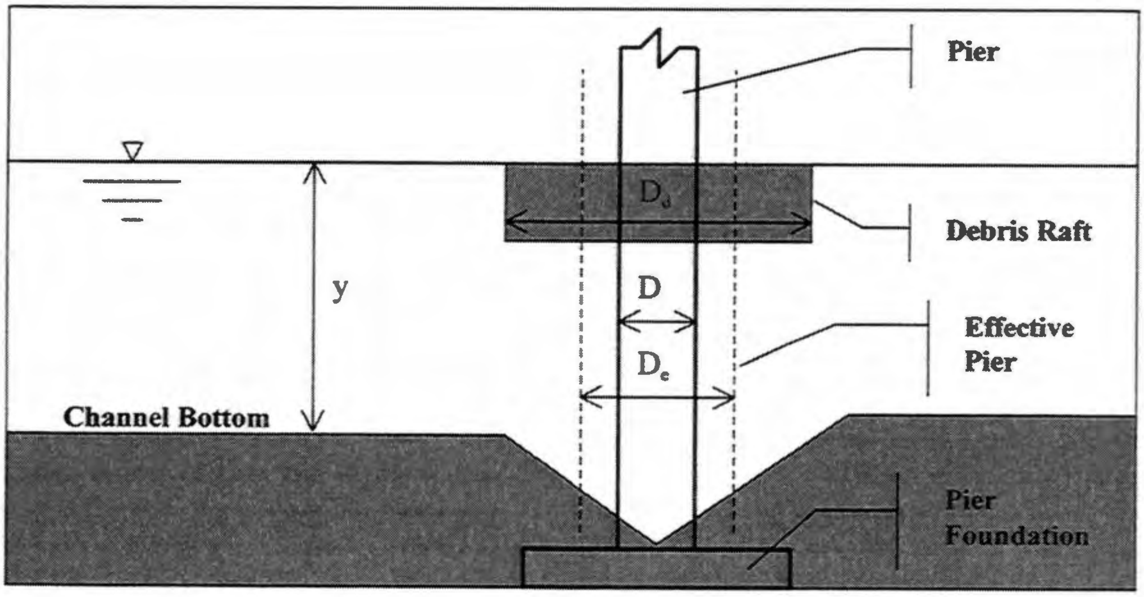


Figure 4. Bridge pier scour with drift accumulation. (adapted from Melville and Dongol, 1992)

T_d* is the effective length of the debris raft (ft), defined by

$$T_d^* = 0.52T_d \tag{6}$$

where T_d is the depth of the debris raft (ft). Values of scour depth at the pier were observed to increase as much as 50% (Melville and Dongol, 1992).

Floating debris accumulations will increase the water surface elevations upstream from the site, a phenomenon known as backwater afflux (Wallerstein, 1996a). Results of a laboratory hydraulic study (Gippel *in* Wallerstein, 1996a) have proposed the following equations to determine afflux created by individual pieces of LWD:

$$\Delta h = \frac{h_3\left[\left(\mathbf{F}^2 - 1\right) + \sqrt{\left(\mathbf{F}^2 - 1\right)^2 + 3C_D B\mathbf{F}^2}\right]}{3} \tag{7}$$

where: $\Delta h = h_1 - h_3$ = backwater afflux due to LWD (m); h_1 = water depth upstream of floating debris accumulation (m); h_3 = water depth downstream of floating debris accumulation (m); C_D = the drag coefficient; and the Froude number (**F**) downstream:

$$\mathbf{F} = \frac{V_3}{\sqrt{gh_3}} \tag{8}$$

where: V_3 = mean velocity at the section downstream of the floating debris accumulation (m/s). The blockage ratio (B) can be determined:

$$B = \frac{L_D d}{A} \tag{9}$$

where: L_D = length of the debris accumulation in the direction of flow (m); A = flow cross-sectional area normal to the direction of the flow (m^2); and d = diameter of the LWD (m). The drag coefficient (C_D) for the debris accumulation can be calculated by:

$$C_D = \frac{2F_D}{\rho V_1^2 L_D d} \tag{10}$$

where: : F_D = dynamic force of flowing water (N); V_1 = mean velocity at the section upstream of the floating debris accumulation (m/s). It should be noted, however, that this calculation of the drag coefficient assumes infinite flow boundary effects. Backwater afflux can be determined with Equation 7 for individual pieces of LWD, but judgement will ultimately dictate in the estimation of afflux created by an entire floating debris accumulation.

Wallerstein (1999) uses the following equation to calculate the hydrostatic forces translated to the bridge substructure through the floating debris accumulation:

$$F_p = A_D \rho_w g C \tag{11}$$

where: F_p = hydrostatic force (lbf); A_D = area of the floating debris accumulation (ft^2); and C is the depth from the water surface to the centroid of the area of the floating debris accumulation (ft). A common assumption is that the floating debris raft has vertical sides, and thus the vertical distance to the centroid would be simply $T_d/2$.

The AASHTO LRFD specifications (1998) recommend dynamic stream force on the substructure of a bridge be evaluated by:

$$F_D = AC_D \frac{\gamma}{2g} V^2 \qquad (12)$$

where: F_D = dynamic force of flowing water (lbf); C_D = drag coefficient; A = flow cross-sectional area normal to the direction of the flow (ft^3); and γ = specific weight of water (lb/ft^3). The drag coefficient, C_D, is typically in the range 0.7 - 1.4 for various pier shapes, and can be calculated for debris accumulations with Equation 10 if drag force values and drift dimensions are known. AASHTO recommends the assumption of 0.5 for the drag coefficient as a guide. Thus, the actual pressure of flowing water will be lower, but will affect the entire debris raft cross-sectional area, and will thus translate a greater stream force to the bridge substructure.

For culverts, the effects of floating debris accumulations differ, depending on the shape, material, and whether the culvert is experiencing inlet or outlet control. The Washington State Department of Transportation (WSDOT) Hydraulics Manual (1997) states "the culvert site is a natural place for [floating debris] to settle and accumulate". For typical situations, Normann and others (1985) indicate that floating debris will tend to gather around the culvert inlet or become lodged within the barrel, reducing flow capacity and resulting in flooding; "... causing damage to upstream property. Roadway overtopping will create a hazard and an inconvenience to traffic and may lead to roadway and culvert washouts" (Normann and others, 1985).

McEnroe and Johnson (1995) describe the drift accumulation mechanics at culverts: "Debris too large to pass through the culvert accumulates at the water surface around the inlet. As the headwater rises, the top of the inlet traps some of this debris; the rest floats on the water surface above the inlet [providing that adequate freeboard exists]. At higher discharges, the debris around the inlet is compacted and drawn further into the culvert. As the storm flow recedes and the headwater falls, the floating debris settles in front of the inlet. After a flood, a culvert may be entirely covered with debris." The deposition of drift at a culvert inlet thus has the potential to produce a greater future capacity reduction unless proper maintenance is performed.

During McEnroe and Johnson's (1995) investigation of the hydraulics of flared-end section culverts, an unexpected effect of floating debris blockages during inlet conditions was observed; the flow through the culvert is actually optimized by shifting from inlet control to full flow. This behavior is explained when focusing on the disruption of the downward momentum of the inflow and its associated vortex. This disruption in the flow pattern around the inlet allows a greater horizontal momentum component that eliminates the "sag" in the water surface profile immediately within the culvert, i.e. full flow. McEnroe and Johnson recommend incorporating horizontal "flow bars" on flared-end sections to produce this special effect of floating debris during inlet conditions, even if floating debris is not present.

For outlet conditions, McEnroe and Johnson (1995) indicate that floating debris will increase the entrance loss coefficient, and thus reduce the culvert's capacity. The investigations determined that flared-end section culverts have entrance loss coefficients in the 0.24-0.31 range, while noting that a typical entrance loss coefficient for culvert design is 0.5. The researchers then established entrance loss coefficient for culverts with floating debris to be in the range 0.65 - 1.05, more than double that which is typically assumed.

Prevention and Mitigation of Floating Debris

Due to the harmful effects of floating debris at bridges and culverts, man has sought to prevent, minimize, or at least mitigate its accumulation at these structures. The primary focus of floating debris-induced damage prevention and mitigation in literature exists on four levels: passage, interception, deflection, and maintenance. Passage is a design or structural retrofit solution that allows for the passage of drift through the hydraulic structure in order to prevent accumulation. Interception and deflection of floating debris revolves around some method, typically structural, of retaining or diverting, respectively, floating debris before it reaches the hydraulic structure. Maintenance issues focus on the general upkeep of the hydraulic structure, plus removal of deposited drift after a major storm event.

Reihsen recommends in the well-referenced HEC-9 "Debris Control Structures" (1971) the evaluation of the following considerations when planning a floating debris control structure:

1. Type of expected floating debris (i.e., urban trash, LWD, etc.)
2. Quantity of expected drift.
3. Future changes in floating debris type or quantity.
4. Stream flow velocities in the area of the hydraulic structure for the design storm event.
5. Topographic information of the site for debris retention capabilities.
6. Possible damages resulting from floating debris blockage of the hydraulic structure.
7. Standard or frequency of maintenance.

Site characteristics may also play a considerable role in the design of floating debris control structures. A high embankment may allow for greater headwater, but may also make maintenance more difficult (Reihsen, 1971).

Many structures are designed to encourage the passage of drift through the hydraulic structure in order to prevent accumulation. Normann and others (1985) recommend achieving passage of floating debris through "provision for a smooth, well-designed inlet and avoidance of multiple barrels and skewed inlets" and also "by oversizing the culvert or utilizing a bridge as a replacement structure." Reihsen (1971) remarks "often the waterway opening is arbitrarily increased in an attempt to pass debris." However, the additional cost of an oversized structure may be prohibitive (Reihsen, 1971)(Normann and others, 1985).

One strategy to balance cost effectiveness with floating debris passage efficiency is a structure that aligns drift with the longitudinal axis of the bridge opening or culvert for ready passage through the structure. A common form of this device is the debris fin as shown in Figure 5. Debris fins are typically thin walls of concrete that extend upstream from the hydraulic structure, installed parallel with the flow to align drift and avoid increasing the projected pier width (Reihsen, 1971). Debris fins are often sloped upward toward the hydraulic structure to allow any drift that does not readily pass through the structure to "ride up" with the water surface and avoid blockage. The importance of a debris removal maintenance program after large storm events is obvious (as shown in Figure 5).

The USACE Clover Fork Diversion Tunnel project (Martin, 1989), near Harlan Kentucky, implemented both a two-dimensional finite difference model and a physical model to simulate flow conditions with floating debris and to design the most effective entrance conditions. The transitional sections from natural channel to entrance channel were found to assist drift alignment best when curved, preventing flow separations and eddying. The study also found that "blunt edges and flat surfaces at or below the water surface tend to cause turbulence and gather debris, [while] sloping noses with circular shaped sections helped prevent debris from lodging" (Martin, 1989).

Figure 5. Debris fins with drift accumulation. (from Tennessee Department of Transportation, 1998)

Interception of floating debris is a common method of preventing blockage of hydraulic structures by retaining drift upstream of the site. The trash rack, used primarily for culverts is perhaps the most common interception device in use (Reihsen, 1971). Trash racks (also known as debris racks) are barriers, typically constructed out of parallel or gridded bars of steel, that do not allow drift of a certain size to enter the culvert or bridge opening. A significant amount of headloss and backwater effects can be experienced by flow through a trash rack, especially during design storm events when floating debris loading is heavy (Wallerstein, 1996b). The American Society of Civil Engineers and Water Environment Federation (1992) instructs in a manual of practice that the net open surface area of the trash rack should be at least four times the cross-sectional area of the culvert. The manual of practice also indicates that safety issues such as bar spacing and entrance velocities must also be taken into consideration during the design process.

Abt et al (1992) studied the efficiency of various trash rack slopes and found that a 2:1 (horizontal to vertical) sloped rack will tend to clog, while a 3:1 sloped rack will remain relatively drift free. This corresponds to the American Society of Civil Engineers and Water Environment Federation (1992) guidance that trash racks be sloped at 3:1 to 5:1, allowing the floating debris to "ride up" as the water level rises above the culvert inlet.

Abt and others (1992) also refer to the fact that engineers typically assume up to a 50% debris blockage when designing a culvert. For the special case of supercritical flow, it is possible that floating debris has a lesser effect on localized flooding than non-floating debris. Abt and others investigated trash rack blockages in supercritical flow situations and have found that "debris placed in the top portion of the flow, at and near the water surface, resulted in localized flooding at 58% blockage, while debris placed adjacent to the channel bed caused flooding at 41% blockage." Thus, a simple blockage assumption, even up to 50%, may not always be appropriate or conservative, especially in cases where supercritical flow is present.

Another example of an interception device is reported by Wallerstein and others (1996b) at a location in the Bavarian Alps. The "Treibholzfange" debris retention device consists of a series of circular posts set into the channel bed upstream of a site plagued by historical drift accumulation problems. A planform view of two such debris retention devices is shown in Figure 6.

Various configurations of posts were tested in a flume to determine the best retention efficiency with the minimum headloss. The posts form a "V" shape directed downstream, with post spacing set by the minimum length of debris that was intended to be trapped. An energy dissipation pool was included downstream of the posts, with provision to allow some sediment transport to prevent degradation of the downstream stream reach. The method of debris removal from this device was not discussed.

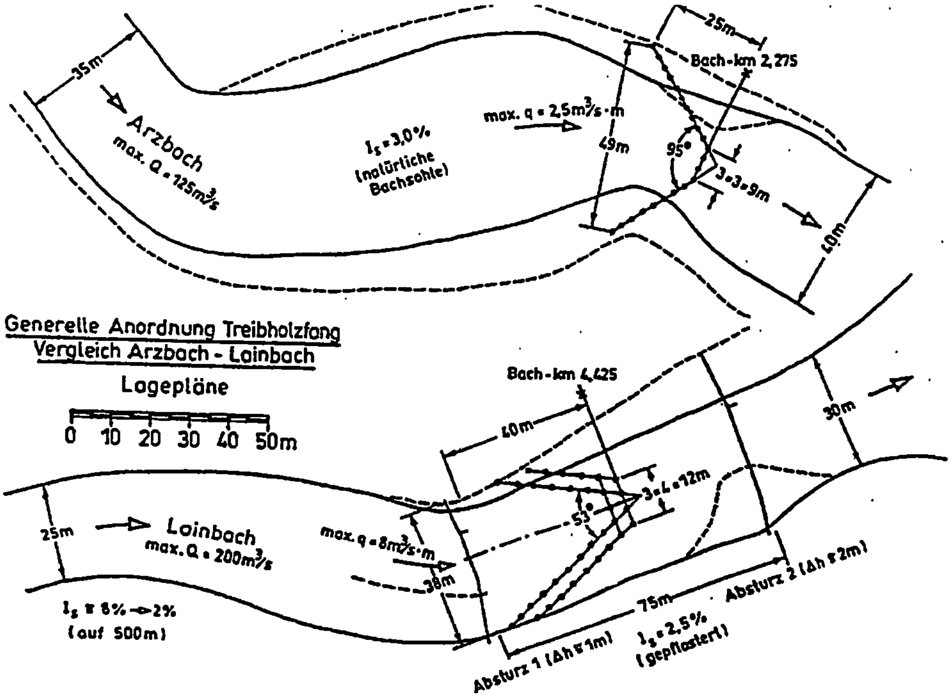


Figure 6. Planform view of the "Treibholzfange" debris retention device. (from Wallerstein, et al. 1996b)

Deflection of floating debris is accomplished by diverting the path of the drift from the hydraulic structure inlet to some other location, typically a retention basin suited as a holding area (Normann and other, 1985). Simple debris deflectors are inclined steel bars or rails, whereas more complex structures (often "V" shaped, pointing upstream) are required for bridges and larger culverts (Reihsen, 1971). After the storm event, the deposited drift would then be removed. In order to facilitate debris removal, Reihsen suggests that adequate storage be accounted for in the holding area, anticipating the quantity of drift and the period between cleanouts, and also by designing for ease of access for maintenance crews.

Booms are also implemented in the effort to deflect floating debris to the side of a channel into a holding area. Perham (1988) presents a collection of end-view and elevation sketches for various styles and configurations of booms. Booms have been used for years in the pulpwood industry, and are primarily wooden in construction, but may also be fashioned out of steel.

Sadler (1999) reports on the considerations associated with the design of a fixed glance rack (boom) to be located on the upper Cumberland River in rural eastern Kentucky. Floating debris blockages had been observed at bridges and piers in the area, and had also made several boat landings inaccessible. "The system consists of a fixed glance rack extending approximately 100 feet into the Cumberland River at a thirty degree angle to the flow" (Sadler, 1999). The angle of attack is intended to promote gradual drift transport form the channel to the shore, while minimizing both lengths of material and impact forces. The rack then extends onto the shoreline in order to direct the captured debris into a holding area.

For the floating debris management approaches of interception and deflection, both raise the issue of maintenance and disposal of the deposited debris after large storm events. Cleaning or "snagging" the channel of deposited debris after a storm event has been common practice for reducing the effects of floating debris (Shields and Gippel, 1995), but this practice has recently come under fire for causing adverse ecological and sediment transport impacts within the riverine system (Gurnell, 1997). Smith and Collopy (1998) states "removal of woody debris from streams ... reduces the supply of food and stable substrates for benthic organisms and reduces retention of the detritus that other invertebrates eat."

The removal of drift depositions near bridges and culverts is often achieved through maintenance crews utilizing cranes with clamshell buckets or similar equipment (Perham, 1988). The efficiency of a structural floating debris countermeasure, such as a trash rack, may actually increase the need for drift removal. Diehl (1997) observes "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." Rebecca Burns of PennDOT (1999) concurs, stating "Trash racks are an acceptable method to prevent problems in culverts, but they also create additional maintenance work of removing debris from the rack on a periodic basis." Thus, maintenance must be a primary consideration when faced with floating debris problems at bridges and culverts.

After the drift depositions have been removed from the site, the matter of disposal remains. Perham (1987) recommends the burning or burial of collected drift as means of disposal, carefully noting "debris should never be placed in areas where it may be carried away by streamflow or where it blocks drainage of an area." More innovative options do exist for useable materials, however, including the separation and processing of the collected debris into firewood and mulch for sale (Sadler, 1999).

III. Gaining Perspective: A Survey of State Bridge Engineers

In order to gauge the current views of debris accumulation in the professional engineering community, a questionnaire was recently sent to the state bridge engineer of each department of transportation in the United States. This audience was chosen because it would reflect the opinions and situations of those who design and maintain the majority of the primary bridges and culverts in the United States (i.e., those associated with the highway infrastructure). Not only does the audience as a group represent a wide range of geologic, hydrologic, and vegetal conditions, but, individually, several states are also quite diverse. Responses were elicited from twenty-seven of the fifty state bridge engineers, plus six district bridge engineers.

The survey of state bridge engineers was distributed by both conventional mail and followed up with electronic correspondence to all 50 states. Most of the addresses, both postal and electronic, had come from the various state departments of transportation internet homepages. The majority of the responses had returned through the mail, however, electronic responses in the form of attachments to email messages were the most rapid responses received.

Survey Questions

The survey concentrated on five topics associated with floating debris accumulation at bridges and culverts:

- incidence of floating debris accumulations and related damages,
- cost of deposited debris damages and removal,
- structure of debris removal maintenance programs,
- design and analysis considerations, and
- countermeasures against floating debris damage.

A sample survey form can be found in Appendix A. Responses were received from 27 state bridge engineers of the 50 solicited, with the Arkansas Highway and Transportation Department (AHTD) including responses from six of its ten district bridge engineers. The questionnaire-elicited responses ranged from simple one-word answers to very detailed responses, which gave great insight into the opinions of the respondents. Each question included an area for the respondent to include additional commentary.

The first question asked if the state bridge engineer considered floating debris and its associated blockages at bridges and culverts to be a major problem in his or her state. This question had a dual-purpose, to gain insight into the opinion of the state bridge engineer towards floating debris as a priority, and to be able to recognize incidence of drift accumulations.

Cost is an overlooked factor in the protection of bridges and culverts from floating debris accumulations and the damages thereby induced. In order to begin gaining perspective on the financial magnitude of the problem, the respondents were asked for their annual budget for bridge and culvert maintenance under their jurisdictions. Then, a follow-up question inquired into the estimated percent of that budget that is allocated for debris removal and repairing debris related damages. Percentage of budget is a preferable value instead of actual dollar amount due to the wide variation in the number of bridges and culverts from state to state.

A request for a description of the maintenance program to remove debris from bridges and culverts was the next item on the questionnaire. The respondent was prompted to specify whether debris removal was periodic or done on a case-by-case basis. A request for a copy of the relevant maintenance program was made.

The fourth question asked the respondent if floating debris is taken into consideration during the structural or hydraulic design and analysis of bridges and culverts in their jurisdiction. Trash racks, extra wide spans, and pier shape and type were listed as examples of structural design considerations.

The topic of the effectiveness of various floating debris countermeasures was addressed as the final question on the survey to the State Bridge Engineers. As examples of some of the various countermeasures to consider, bank clearing maintenance, skimmer booms, trash racks, clear cutting regulations, and trash education/awareness programs were listed.

Summary of Findings

Responses were received from 27 state bridge engineers of the 50 solicited, and the Arkansas Highway and Transportation Department (AHTD) furnished additional responses from six of its ten district bridge engineers. The respondent states are shown in Figure 7. The wide range of topics covered by this questionnaire and the relatively sparse available hard data caused Rebecca Burns of the Pennsylvania Department of Transportation (PennDOT) Bureau of Bridge Design to comment "you have asked several questions which are difficult, if not impossible, to answer." This difficulty is perhaps the primary reason that more surveys were not returned.

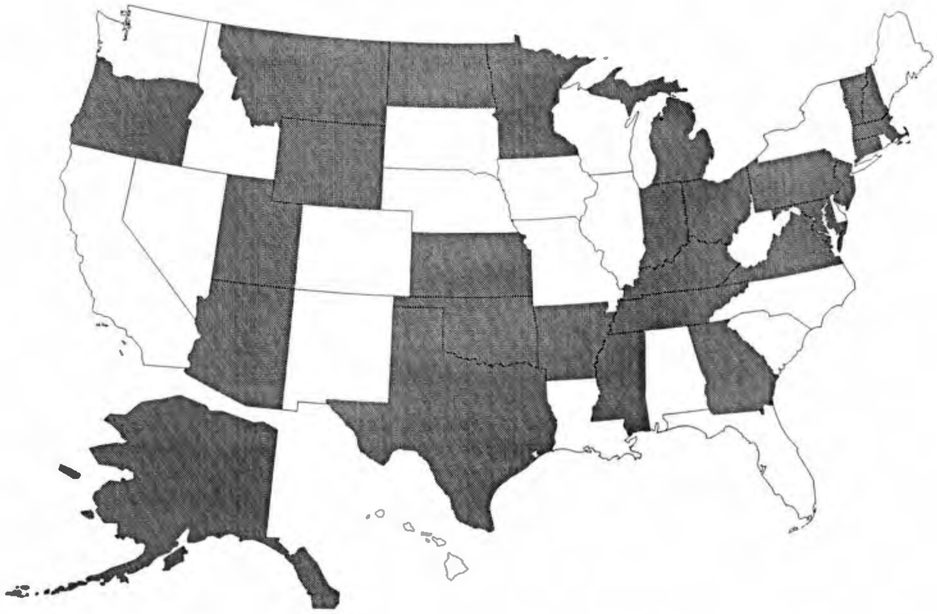


Figure 7. Respondents of State Bridge Engineer Survey. (indicated by shading)

The first major discovery due to the survey questionnaire is the widely decentralized knowledge base regarding floating debris at many of the state departments of transportation. The variations in floating debris quantities from one region to another, within an individual state, has led many of the state bridge engineers to allow the district bridge engineers to handle floating debris problems on a district basis. Without centralized systems to track floating debris problems, the collection of relevant data is nearly impossible without contacting each District Bridge Engineer. This would be a daunting task when considering the sheer number of district bridge engineers nationwide.

Survey responses are summarized below, while the full responses can be found in Appendix A. Due to the nature of some of the answers, some interpretation was required for categorization purposes. In the discussion below, the respondent will be indicated by the two-letter postal abbreviation for the state. Responses of the Arkansas District Bridge Engineers can be found in Appendix I (AR2 – AR10).

1. *Is floating debris and its associated blockages at bridges and culverts a major problem in your state?*
   - **Yes** - KY, MA, MN, MS, OH, OK, OR, PA, TX, UT, VT **(11)**
   - No – AK, AR (all districts), AZ, CT, GA, IN, KS, MD, MI, MT, ND, NH, NJ, TN, VA, WY **(16)**

The general consensus of the responses was that floating debris can be a problem; however, it was not deemed to be a major problem. No regional trend is readily apparent in the distribution of answers, as shown in Figure 8. Two of the respondents that

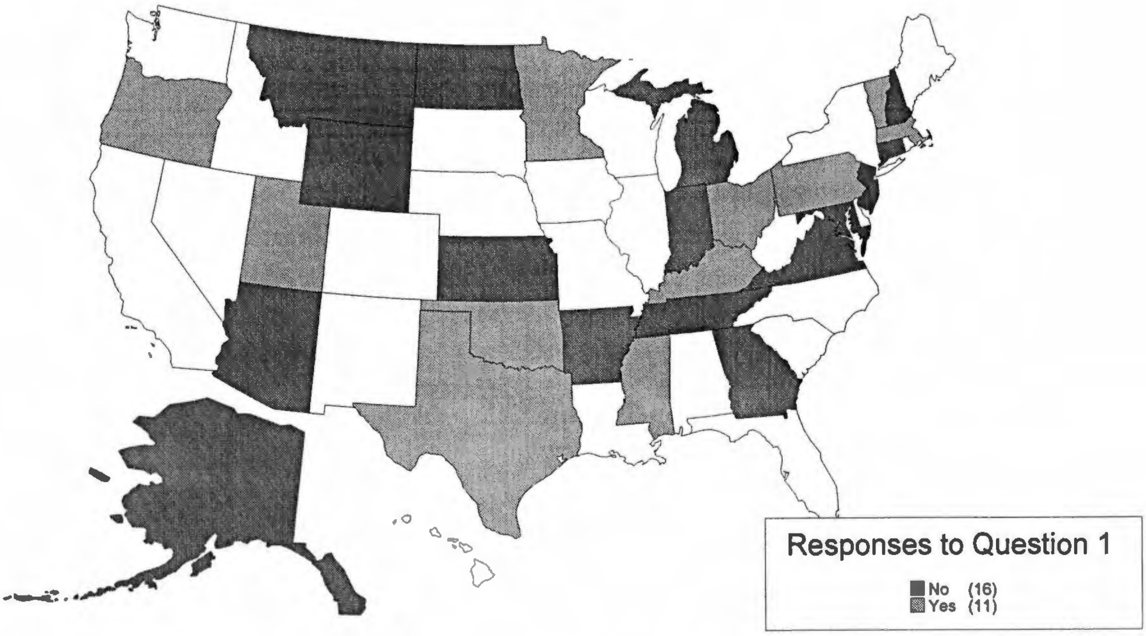


Figure 8. Distribution of Responses to Question 1. ***Is floating debris and its associated blockages at bridges and culverts a major problem in your state?*** (indicated by shading – see insert)

indicated floating debris is a major problem referred to local logging practices in the problem areas. John Allen of the Minnesota Department of Transportation was observant to note "Yes - but major problems are associated with major floods. Debris accumulations during non-flooding are removed by Maintenance forces and are a minor problem." Massachusetts has recently completed its Scour Critical Bridge Program, which indicated that 22% of its 2357 bridges are categorized with high potential for drift accumulation. PennDOT correspondingly indicated that 26% of its 6400 bridges have a need for debris/vegetation removal. Reviewing the commentary attached to many of the responses, it was found that 81% of the bridge engineers indicated that a floating debris problem, irrespective of magnitude, existed in their state. Thus, floating debris is generally deemed to be a minor to moderate problem.

2. *What is the annual budget for maintenance of bridges and culverts under your jurisdiction? Approximately what percentage is allocated for debris removal and repairing debris-related damages?*

Results are shown in Table 2.

Budgetary information seems to be the most difficult data to acquire, primarily due to the decentralized nature of debris removal. Most debris removal is performed by district maintenance forces or through subcontracting on the district level, without some sort of reporting mechanism to the state bridge engineering office. The budgetary figures do vary quite significantly, which may indicate that the lower values (i.e., North Dakota with $450K) may represent only one district and not the entire state. Only eleven respondents offered estimates of the percentage of annual bridge and culvert maintenance budget allotted to debris removal. The highest percentage reported was in Texas, where approximately 30% of the Bridge maintenance budget is allocated towards bridge channel and under bridge maintenance. Ostensibly, debris removal may only comprise a percentage of those monies. The most commonly reported percentage of budget allocated towards debris removal by state DOT's is less than one percent. No regional trend is readily apparent in the distribution of answers, as shown in Figure 9, however, a slight grouping of responses indicating less than one percent is present in New England.

Table 2. Responses to financial question in survey of state bridge engineers. (N.A. = Not Available, N.R. = No Response to this question)

Question 2: What is the annual budget for maintenance of bridges and culverts under your jurisdiction? Approximately what percentage is allocated for debris removal and repairing debris-related damages?

State	Bridge & Culvert Maintenance Budget	Estimated percentage of Bridge & Culvert Maintenance Budget allocated for debris removal.	Comment included (C)
AK	$5M	10%	
AR	$5.2M	5.7%	C
AZ	N.A.		C
CT	$7M	<1%	
GA	$15M	<1%	
IN	varies		C
KS	N.A.		C
KY	$22M	N.A.	C
MA	N.A.		C
MI	N.A.		C
MD	N.R.		
MN	$3-4M	small percentage	C
MS	N.A.		
MT	$1.6M	unknown	
ND	$450K	none	
NH	$6M	<1%	
NJ	$7M	none	
OH	N.A.		C
OK	N.A.		C
OR	$4.5M	5-10%	C
PA	N.R.		
TN	$30-35M	N.A.	C
TX	$18M	30%	C
UT	N.A.		
VA	N.A.		
VT	$3.1M	<1%	
WY	N.A.		C

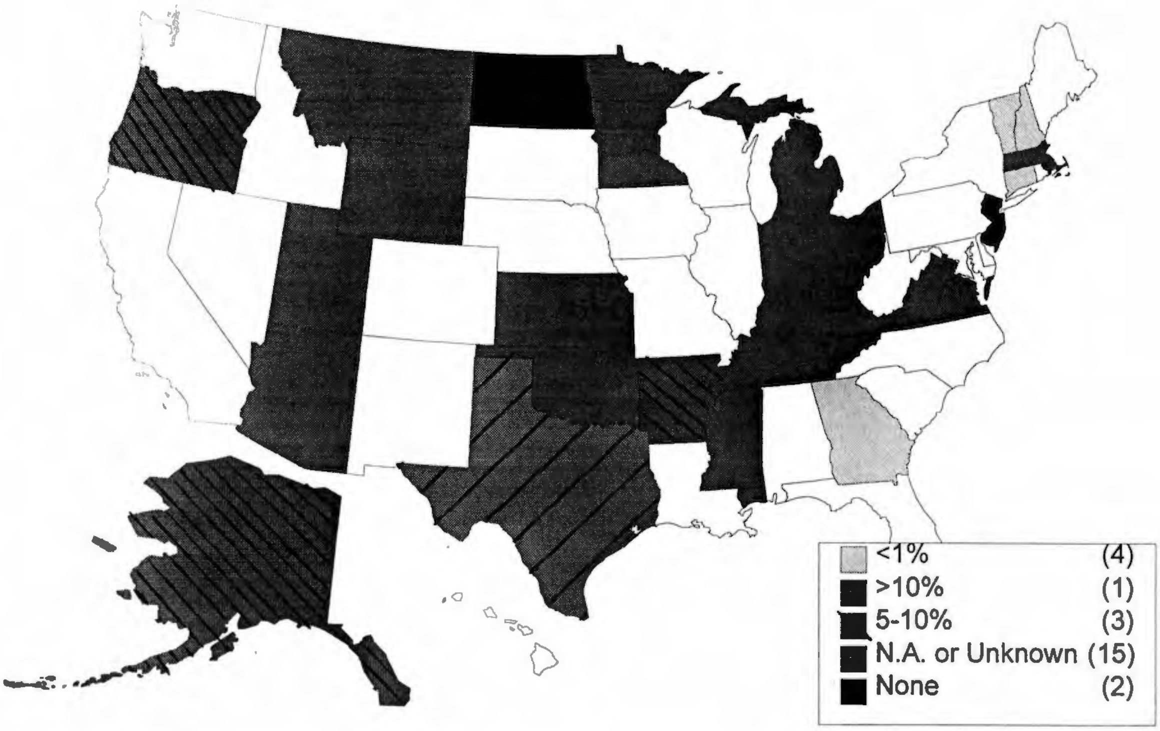


Figure 9. Distribution of Responses to Question 2. *Approximately what percentage (of your annual budget for maintenance of bridges and culverts) is allocated for debris removal and repairing debris-related damages?* (indicated by shading – see insert)

Financial information alone, however, does not necessarily reflect the state of floating debris damage or damage prevention in a region. A successful and efficient maintenance program may lead to lower expenditures and require less financing, but may be superficially perceived as not sufficiently pursuing floating debris prevention. On the other hand, a large budget expenditure may indicate either a progressive and forward facing floating debris maintenance program, or may reveal a completely inadequate system that wastes money by misdirecting resources. To be able to better resolve this issue, a comparison of the responses was performed, as shown in Table 3. The responses

Table 3. Comparison of Responses to Questions 1 and 2.

Response Question 2 Question 1	> 10%	5-10%	< 1%	None	Not Available or Unknown
Yes	TX	OR	VT		KY, MA, MS, OH, OK, UT, MN
No		AK, AR	CT, GA, NH	ND, NJ	AZ, IN, KS, MI, MT, VA, WY, TN

were generally evenly distributed, however, the vast majority of the 0-10% allocation respondents had also indicated that floating debris was not a major problem in their state.

Urban floating debris programs also have costs associated with them. The author, as a side note to this survey, contacted David Hagerman, stormwater engineer with the City of Knoxville, to illustrate the costs of a mid-sized city's floating debris maintenance program. Hagerman (1999) explains, "I don't have specific numbers for that task but one thing that may get us close is the cost of the 4 man creek crew. This crew is specifically assigned and dedicated to removing trash and debris from the all the city creeks on a routine schedule. The funding for the annual period from July 1, 1998 to June 30, 1999 is as follows: Labor $67,103.65; Equipment $6,921.45; Materials $1,884.11; Total Cost $75,909.21." Figure 10 shows the Knoxville four man creek crew removing a floating debris accumulation from the Second Creek embayment. Note the large pieces of woody debris apparent in this urban drift accumulation.

Figure 10. Floating debris accumulation removal in Knoxville. (Photo courtesy of Hagerman)

3. Describe your organization's maintenance program to remove debris form bridges and culverts (i.e., periodic or case-by-case, etc.).

- **Case-by-case** – AK, AR, AZ, CT, GA, KS, KY, MA, MD, MI, MN, MS, MT, NH, NJ, OH, OK, OR, TN, TX, UT, VA, VT, WY **(24)**
- **Routine maintenance** – AR, IN, ND **(3)**
- **Routine inspection program** – AR, AZ, CT, GA, KS, MA, MI, MN, NH, TX **(10)**
- **Inspection after heavy storms** – AR, MA, MN, NH, OR **(5)**

Perhaps the most consistent insight gleamed from the survey was the description of debris removal maintenance programs. By far, the majority of the respondents indicated that debris removal programs are handled on a case-by-case basis. For many of the respondents, periodic bridge inspection teams indicate which bridges need debris removal and the district maintenance forces or contractors then remove the obstructions. In some cases, it was also indicated that inspection teams visit problematic sites immediately after storm events to determine the need for debris removal.

A comparison of the responses to Questions 1 and 3 leads to a near even distribution, as shown in Table 4. A progressive maintenance program may either be established to mitigate a major floating debris problem, or a major problem may have been averted due to an existing maintenance program. Likewise, a case-by-case maintenance program may be all that is required to prevent a major floating debris problem. Unfortunately, adequate resolution is not available to distinguish these possibilities.

Table 4. Comparison of Responses to Questions 1 and 3.

Response Question 3 Question 1	Case-by-Case	Case-by-Case & Routine Inspections	Case-by-Case & Post-Storm Inspections	Case-by-Case & Routine Inspections & Post-Storm Inspections	Routine Maintenance
Yes	OR, MA, MS, OH, MN, PA	VT, TX, UT	OK	KY	
No	CT, IN, MT, VA, ND, MD, TN	AR, KS, NH, NJ		AZ, GA, MI	AK, WY

4. *Do you consider floating debris in the structural or hydraulic design and analysis of bridges and culverts? How? (i.e., trash racks, extra wide spans, pier shape and type, etc.)*

- **Increased span length / oversizing structure** – AK, GA, KY, MA, MD, ND, NH, OH, OK, PA, TN, VT, WY **(13)**
- **Minimize amount of in-water substructure**– AR, IN, NH, OK, OR **(5)**
- **Pier type & shape** – AR, IN, KS, MA, MI, OH, OR, PA, WY**(9)**
- **Pier / abutment alignment with flow** – GA, MA, TN **(3)**
- **Increased freeboard** – AR, MI, ND, VT **(4)**
- **Wider than normal piers** - AZ **(1)**
- **None** (except AASHTO requirements) – CT, NJ, TX, VA **(4)**

Floating debris-induced scour and increased loads on piers are unlisted considerations for all respondents, as they are dictated by AASHTO specifications. Viewing the responses to this question, it is apparent that most states (23) incorporate some sort of floating design consideration in the design and analysis of bridges and culverts. Providing a clear span to allow floating debris passage is a dominant consideration of floating debris in the hydraulic and structural design of bridges. In the instances where it is impractical or impossible to avoid the placement of a pier in the water, pier type and shape dominate the design considerations for floating debris protection. One instance of pier type and shape considerations in pier design is illustrated in the Kansas Department of Transportation's Bridge Design Manual (1999), shown in Appendix A. The design sketches indicate that round piers are preferred with a non-structural web wall connecting the individual piers in the direction of flow to prevent floating debris from becoming lodged on an internal pier. Aligning piers and abutments with the direction of flow reduces the projected width of piers and lessens the likelihood of floating debris accumulations. Additional freeboard allowances are also implemented for both bridges and culverts to reduce the potential for overtopping of the structure.

Based on survey data, ice flows appears to be a similar and dominating consideration in the northern states. John Allen of the Minnesota Department of Transportation notes "Although we don't specially design for debris, we do design for ice loads which provides reserve structural strength to help resist debris loads." Pier designs may also serve a dual purpose for both ice and floating debris protection, as Rebecca Burns of PennDOT points out "some of our older structures are equipped with armored pointed nose piers which were presumably for breaking up ice, but may be effective on debris rafts as well."

5. *What type of floating-debris countermeasures do you find most effective and cost efficient? (i.e., bank clearing maintenance, skimmer booms, trash racks, clear-cutting regulations, trash education/awareness programs, etc.)*

- **Maintenance at structure** – AK, AR, CT, IN, NH, NJ, UT **(7)**
- **Bank clearing** – CT, TX, VT **(3)**
- **Drift passage (oversizing structures)** – MD, ND, TN **(3)**
- **Reduced in-water substructure**– OR, TN **(2)**
- **Pier type & shape** – KS, MN **(2)**
- **Drift deflection** – MS, OR **(2)**
- **Drift interception (trash racks)** – OH, OR, PA, VT **(4)**
- **Clear-cutting regulations** – TN, VT **(2)**
- **Preventative measure against upstream erosion** - TN **(1)**
- **None specified** – AZ, GA, KY, MA, MI, MT, OK, VA **(8)**

The majority of respondents would not specify an effective or cost efficient floating debris countermeasure. Ford Dotson, the Assistant State Structure and Bridge Engineer for the Virginia Department of Transportation, comments "None of the [countermeasures] are effective or efficient, i.e., this is not a one time solution." The lack of a formal study of floating debris countermeasures prompted Alexander Bardow, P.E., Bridge Engineer with the Massachusetts Highway Department, to note, "The department can not respond to this question, because a comparison of installed debris countermeasures has not been studied. Our response to this question would be purely speculative." Indeed, the site-dependent nature of floating debris accumulations guarantee that one countermeasure will not act as a "fix all" for every situation.

Preventative maintenance through debris removal at the structure and upstream of the site is the primary countermeasure that respondents found effective and cost efficient. As Mark Miles, P.E., State Hydraulic Engineer of the Alaska Department of Transportation and Public Facilities aptly points out "Most of our debris problems are from bank instabilities well upstream of the structures. Other than routine maintenance at the structure, no other countermeasure seems effective or cost effective." Bank clearing upstream of a site is not always an option though, primarily due to the ecological impacts of such activities as William Fullerton, P.E., of the Montana Department of Transportation indicates "Resource agencies would go ballistic if we even suggested bank clearing maintenance." The Tennessee Department of Transportation, however, has adopted a compromise by implementing measures that reduce bank erosion upstream of bridges, thus limiting drift generation.

By reviewing the comments from the 27 responding state departments of transportation, a rough characterization of the status of floating debris at bridges and culverts can be drawn. A general consensus states that:

1. Floating debris can be a minor to moderate problem; however, it is not deemed to be a major problem (59% of respondents).

2. The percentage of the annual bridge and culvert maintenance budget allocated towards debris removal is most commonly unknown or not readily available (48% of respondents), or typically estimated as less than one percent (55% of respondents that estimated a percentage).

3. Deposited debris removal programs are handled on a case-by-case basis (89 % of respondents), where periodic bridge inspection teams indicate which bridges need debris removal and district maintenance forces or contractors then remove the obstructions (37 % of respondents). Several states investigate bridges that have a tendency to accumulate drift for floating debris blockages during, or immediately after, large storm events (19 % of respondents).

4. Along with floating debris-induced scour and increased loads on piers, considerations that are dictated by AASHTO, providing a clear span to allow floating debris passage is the dominant consideration of floating debris in the hydraulic and structural design of bridges (48 % of respondents).

5. Preventative maintenance through debris removal at the structure and upstream of the site is the primary countermeasure that respondents found effective and cost efficient (26 % of respondents). However, many of respondents would not specify an effective or cost efficient floating debris countermeasure (30% of respondents).

By viewing these results, we can interpret a common opinion of state bridge engineers that the most efficient way to approach floating debris accumulations at bridges and culverts is to operate on a case-by-case basis at the local level. This approach, however, has lead to a widespread failure to observe the costs associated with floating debris removal, repair of damages, and maintenance. Local site maintenance is implemented along with some general design concerns (such as in-water pier avoidance) in order to reduce the frequency of drift accumulations. Problematic bridges still do exist in most regions, but are largely considered an acceptable inconvenience, with few states implementing structural countermeasures to further protect these structures.

IV. Recommended Analysis Methodology

Many qualitative and quantitative aspects must be taken into consideration in order to evaluate the effects of floating debris arriving at a bridge or a culvert. Literature indicates three major steps are common in the analysis of floating debris: 1) evaluation of the potential quantity of floating debris delivered to the site, 2) approximation of the quantity of floating debris accumulating at the site, and 3) hydraulic representation of the site incorporating the potential floating debris accumulation. This section aims to review each of these steps while focusing on primary considerations for hydraulic analysis incorporating floating debris. When applicable, recommendations are given for the use of appropriate flowcharts and/or models to aid in the analysis process. An illustration showing this recommended protocol is shown in Figure 11.

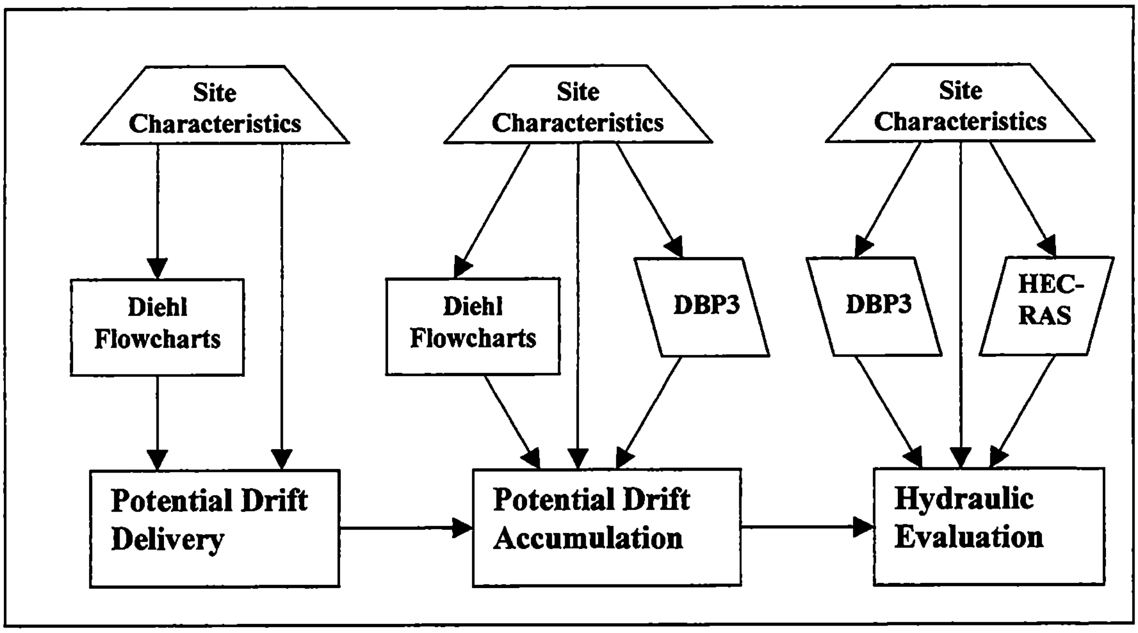


Figure 11. Illustration showing protocol for hydraulic analysis incorporating floating debris.

Potential Drift Delivery

The location characteristics of a site will primarily influence the volume of floating debris delivered to a bridge or culvert. The channel geomorphic character will affect the generation rates of drift, while landuse and tree species will shape the composition and size of floating debris, respectively. The floating debris transportation capability of a site is shaped primarily by the longest stable pieces of drift and the channel width. The volume of debris being delivered to a site then hinges on both the generation rates and the drift transport capability of the location, both of which are largely influenced by site location characteristics.

Topics to consider when evaluating the generation rate of drift revolve around the number of trees that could enter the channel through bank erosion. These items include length of contributing channel, channel evolution and meandering, land use of the contributing drainage area (especially timber cutting), stream power, and slope of the drainage area. Estimations of drift generation may be balanced with observations of drift accumulation near the site, or with more indirect measures noting potential drift production. For example, Diehl and Bryan (1993) suggest the use of aerial photography and maps in the detection of lateral channel migration and widening, which lead to drift production. The incorporation of a Geographical Information System (GIS) as a tool in the prediction and management of floating debris has also been documented (Wallerstein, et al, 1996a).

Drift transport will be affected by any obstruction in the flow path between the generation and the site of interest. Channel width may act as a limiting factor in lesser order streams if the longest stable pieces of drift are wider than the channel. Forested floodplains may act to screen out floating debris and shield an area during extreme storm events.

Proper evaluation of potential drift volume will take both the qualitative and quantitative aspects of a site location into account. As discussed in the Literature Search, simple quantitative estimations of potential drift production are performed in the Debris at Bridge Pier Prediction Program (DBP3) created by Wallerstein (1999). The input variables for this program are riparian tree density, average bank top failure width, and reach length. The program delivers an estimate of the number of trees approaching the site. Diehl (1997) offers logical flow charts to help guide the qualitative assessment of potential for a river to deliver drift. A combination of these two methods, including assessment of more site-particular characteristics will contribute to proper evaluation of potential drift volume.

Potential Drift Accumulation

In order to evaluate the potential for drift accumulation at a bridge or culvert, one must examine the characteristics of the site, bridge or culvert configuration, and floating debris. The values involved in this examination will be a combination of quantitative and qualitative aspects, with substantial consideration given to site-specific characteristics. As discussed in the Literature Search, probabilistic estimations of drift accumulation at a bridge are performed in DBP3. The input variables for this computation are: tree trunk diameter, tree height, number of trees approaching the bridge span, distance between bridge piers, and flow depth. The program presents the probability of one tree becoming trapped and the floating debris raft depth (T_d) and width (D_d), and the percentage of the span cross-sectional are blocked by the debris raft if all trees are accumulated (worst case scenario). Diehl (1997) offers logical flow charts to help guide the qualitative assessment of potential drift accumulation on individual bridge (or culvert) components. A combination of these two methods, including assessment of more site-particular characteristics will contribute to proper evaluation of potential drift accumulation at a bridge or culvert.

Hydraulic Evaluation

The hydraulic effects of floating debris accumulation at bridges and culverts typically involve blockage and scour potential concerns. Wallerstein (1999) lists four possible consequences of floating debris blockages: backwater effects, local flow diversion, channel bed erosion, and structural failure. Each of these effects are largely dependent on the configuration of the bridge or culvert and the approaching channel.

The author is only aware of two models that quantify hydraulic effects at bridges. These two models are the Debris at Bridge Pier Prediction Program (DBP3) created by Wallerstein (1999), and the USACE Hydrologic Engineering Center – River Analysis System (HEC-RAS). The author is unaware of a model that incorporates the hydraulic effects of floating debris at culverts.

DBP3 is a scour potential incorporating floating debris accumulations at bridge piers model, created by Nick Wallerstein at the Department of Geography, University of Nottingham, UK. The program evaluates scour potential with floating debris effects based upon the recommendations of Melville and Dongol (1992). The required input data for this computation are those used for the probabilistic estimation of drift accumulation at a bridge (described above), plus velocity, sediment characteristics, and pier size, shape and alignment with flow.

HEC-RAS is a widely used one-dimensional, steady flow, water surface profile model produced and freely distributed by the US Army Corps of Engineers Hydrologic Engineering Center. The generation of HEC-RAS, version 2.2, includes an option to incorporate the effects of floating debris blockages at bridge piers into the bridge hydraulic computation routine.

The user is required to specify the floating debris raft depth (T_d) and width (D_d) at each pier. The blockage area is simply the product of these two values (i.e., the floating debris raft is assumed to have vertical sides), and is centered on the upstream pier with the top of the debris raft placed at the water surface elevation. By centering the floating debris accumulation on the upstream pier centerline, HEC-RAS is suited for single pier accumulations. Span blockages can also be simulated in the model by setting an half the total debris raft width at each pier.

The HEC-RAS Hydraulic Reference Manual (1998) states "the program [computationally] adjusts the area and wetted perimeter of the bridge opening to account for the pier debris," adding "it is assumed that the debris entirely blocks the flow and that the debris is physically part of the pier." By incorporating floating debris accumulations in this fashion, the model is likely to be conservative in computing flow velocity and thus headloss through the upstream face of the bridge.

By applying the basic principles of hydraulic engineering and using models as tools to assist in comprehension, an understanding of the effects of floating debris accumulations at bridges and culverts can be achieved. The US Army Corps of Engineers has set a precedent by using both a two-dimensional finite difference model and a physical model to simulate flow conditions at a major hydraulic structure where floating debris accumulations were a major concern (Martin, 1989).

V. Example: Ten Mile Creek

In this section, a discussion will follow a hypothetical, illustrative analysis evaluating the quantities of drift and hydraulic effects of a floating debris accumulation at a bridge on Ten Mile Creek in Knox County, Tennessee. The Debris at Bridge Pier Prediction Program (DBP3) will be implemented for estimating quantities of drift and hydraulic effects will be determined using the US Army Corps of Engineers (USACE) Hydrologic Engineering Center's – River Analysis System (HEC-RAS). The 100-year storm event shall be the base condition for this example.

Site characteristics

The Ten Mile Creek watershed is a mostly-developed, fifteen square mile drainage area located in the west Knox County, Tennessee. A recent study by Ogden Environmental and Energy Services, Inc. summarized land use in the watershed as being "best characterized as suburban, with commercial and residential development located throughout. There has been a significant increase in the rate of development in the last 15 years, with commercial and medium-density residential areas as the most rapidly growing land uses" (Ogden, 1999). Like most of Knox county, the watershed has moderately drained soils underlain by a highly karst region. The stream gradient is very steep in the upstream third (0.006 ft/ft), with narrow and steep channels. Throughout the rest of the six-mile reach, the stream gradient is mild (0.003 ft/ft) with wide floodplains that are prone to flooding during extreme rainfall events.

The I-40 / I-75 Interstate Highway corridor crosses the Ten Mile Creek approximately halfway, with approximately three miles of drift-transport-capable reaches contributing flow to the site. The I-40 / I-75 bridge crossing is located almost normal to the streamflow; however, it is located in a south-of-west to due south bend in the channel. Floating debris can thus be expected to accumulate primarily on the outside of the bend, on the right bank looking downstream. The bridge embankment is pronounced, approximately 20 feet higher than the channel bed, as can be seen in Figure 12. This large embankment will prevent overtopping during extreme storm events, but may contribute to considerable backwater effects.

Potential Drift Characteristics, Quantity and Accumulation

The potential for drift delivery and drift accumulation potential on individual elements of the bridge shall be based on the qualitative flowchart method suggested by Diehl (1997), while the actual accumulation at the bridge shall be quantified by the DBP3 model (Wallerstein, 1999).

The potential for drift delivery to this site is limited by several factors. First, a lack of direct evidence of drift accumulations leads to the consideration of indirect evidence

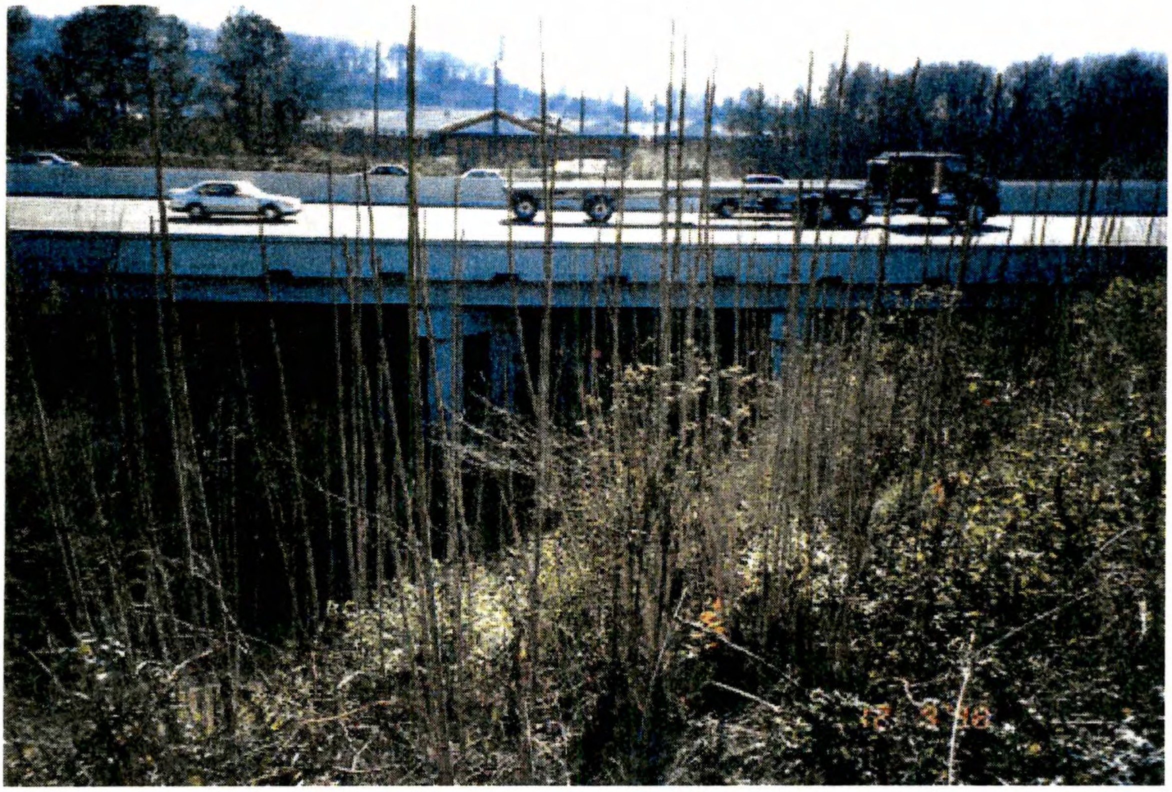


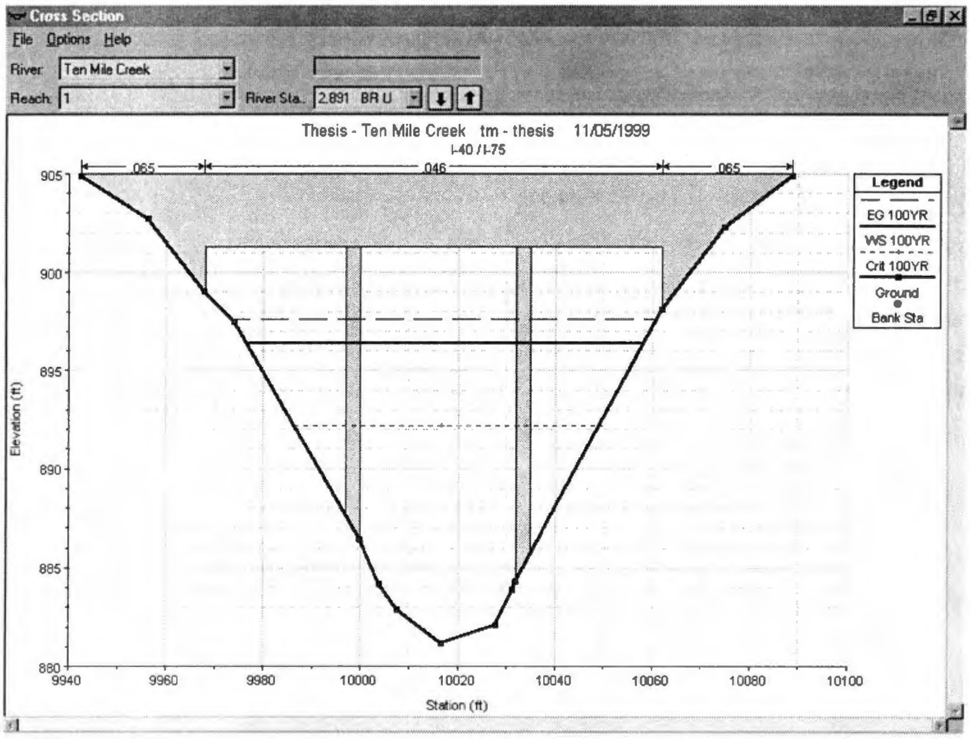
Figure 12. Interstate Highway 40 / 75 bridge over Ten Mile Creek. (Photo courtesy of Ogden Environmental and Energy Services, Inc.)

indicating the potential for future drift generation. The reader is referred to the Diehl flowchart shown as Figure C1 in Appendix C. Indirect evidence would suggest that the stream is not actively evolving or displaying pronounced signs of bank erosion or mass wasting. Meandering, although present in the stream, was not observed to be greatly propagating. Many of the floodplains, however, were wooded, and trees with exposed root systems were noted to populate the channel banks. These trees indicate that some future generation of drift through erosion is possible. The delivery of drift will be limited by the somewhat narrow channel upstream of the site, bounded by wooded floodplains on either overbank. A low delivery potential will be assumed for the purposes of this example.

As discussed previously in the Literature Search, the characteristics of floating debris accumulations are dominated primarily by the species of tree in the region and the channel dimensions. For this region of the country, trees can be characterized as having an average height of 90 feet (27 m) with an average trunk diameter of approximately 3.4 feet (1.0 m) (Diehl, 1997). A realistic assumption of the largest diameter of the stable root ball / crown of the tree would be 20 feet (6 m). By viewing the width of the channel and the configuration of wooded floodplains (that would screen out drift), the realistic assumption that the maximum transportable stable drift length is limited to 40 feet (12 m) is made.

The bridge has two 3-foot (0.9 m) diameter solid rounded piers located at the top of banks of the low-flow channel. These are the only obstructions to the flow and are not sheltered by an upstream forest. The clear span between these rounded piers is 32 feet (10 m). A cross-sectional plot of the upstream bridge face from the HEC-RAS model is shown in Figure 13. The location category of the right pier is termed "In the path" of floating debris, by the Diehl flowchart shown as Figure C2 in Appendix C, while the left pier would be "In the channel."

A span blockage by floating debris is possible at this bridge, as indicated by the fact that the maximum stable drift is longer than the clear between the bridge piers. Because the width between the pier and channel bank is also less than the maximum stable drift length, it would also be likely that floating debris may become lodged in the span



River: Ten Mile Creek

Reach: 1

River Sta.: 2.891 BR U

Figure 13. Cross sectional plot of the upstream bridge face from the HEC-RAS model.

between the bank and a pier. Following the Diehl flowchart shown as Figure C3 in Appendix C, we see that the right pier exhibits a medium span blockage potential, while the left pier is termed to have a low span blockage potential. Similarly, the flowchart presented as Figure C4 in Appendix C indicates that the right pier exhibits a medium pier accumulation potential, while the left pier is termed to have a low pier accumulation potential.

The probabilistic quantification of this floating debris accumulation is performed with the DBP3 model created by Wallerstein (1999). The program allows the user to enter the estimated number of trees arriving at the, otherwise an estimate is made from the input variables: riparian tree density, average bank top failure width, and reach length. Due to the low to medium potential for drift accumulation at the bridge in question, an estimate of three trees was made for demonstrative purposes. Other necessary input values are the tree trunk diameter, tree height, distance between bridge piers, and flow depth. The flow depth of 15 feet (4.6 m) was determined through the HEC-RAS uniform depth at the bridge upstream face without floating debris.

From this program, the probability of one out of the three trees becoming trapped is 100% (because the maximum stable drift is longer than the clear between the bridge piers). If all three trees become trapped, the percentage of the span cross-sectional area blocked will be 25%, with the debris raft depth (T_d) of 3.4 feet (1.04 m) and width (D_d) of 20 feet (6 m). The output of this program is shown in Appendix C.

Hydraulic Modeling with HEC-RAS and DBP3

Hydraulic effects of this floating debris accumulation can be quantified with the steady flow model HEC-RAS and also with the DBP3 program. The existing hydraulic conditions of Ten Mile Creek at the I-40 / 75 Interstate Highway bridge have already been modeled in HEC-RAS for the 100-year storm event (Ogden, 1999). This model, however, did not include the possibility of drift accumulation at the bridge face (drift accumulations are typically not incorporated into a flood study unless specifically budgeted to do so). For more information on the modeling bridges in HEC-RAS, please refer to the HEC-RAS River Analysis System: Hydraulic Reference Manual (U.S. Army

Corps of Engineers, 1998). The results of the HEC-RAS model without floating debris indicated that the flow depth was 15 feet (4.6 m) (as stated above) and the velocity was 7.8 feet per second (2.4m/s) upstream of the bridge.

The incorporation of floating debris into the model was accomplished by utilizing the floating pier debris option in the pier geometry window. As mentioned previously in the preceding section, HEC-RAS centers the drift accumulation on the pier, and thus makes representation of a span blockage difficult to accomplish. In order to achieve this effect, a floating debris accumulation with a width of 35 feet and a depth of 3.4 feet was added to each of the two piers. The debris raft depth value (T_d) recommended in DBP3 was used, but the width (D_d) entered represented the necessary length to achieve span blockage in the model. This assumption is conservative. A cross-sectional plot of the upstream bridge face from the HEC-RAS model including floating debris is shown in Figure 14.

The HEC-RAS plot of the water surface profile comparing the debris and non-debris conditions is shown in Figure 15. A 2.3-ft surcharge due solely to the floating debris accumulation is readily apparent immediately upstream of the bridge. The floating debris accumulation is shown to have an increased effect on the water surface flood elevation almost one mile upstream. Flow velocities at the upstream face of the bridge increased from 9.47 ft/s to 14.04 ft/s, a 48% increase that would be likely to make scour a concern. Flow velocities within the channel generally decreased upstream of the bridge in the

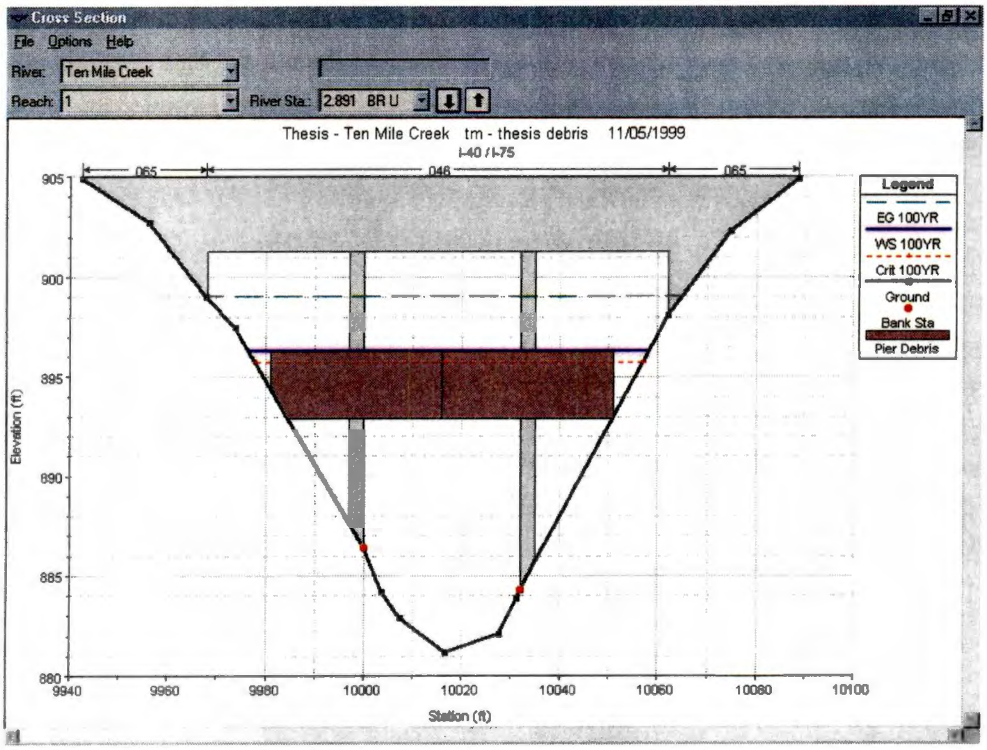

River: Ten Mile Creek
Reach: 1
River Sta.: 2.891 BR U

Figure 14. Cross sectional plot of the upstream bridge face from the HEC-RAS model including floating debris.

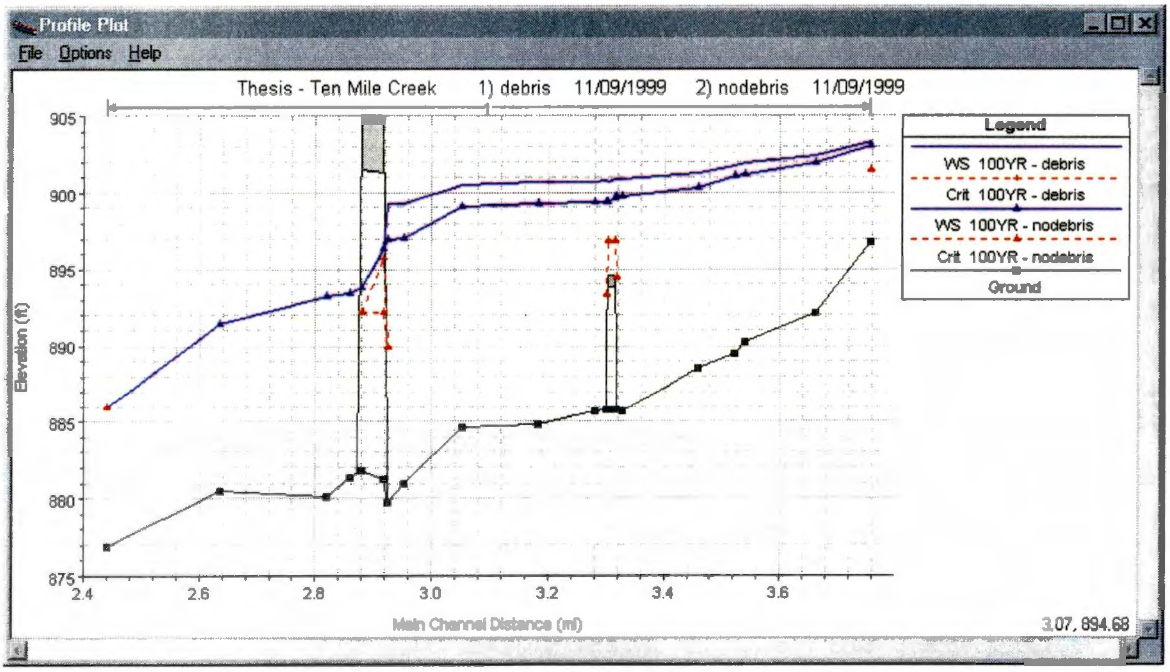


Figure 15. HEC-RAS plot of the water surface profile comparing the debris and non-debris conditions.

floating debris condition, due to the increased flow area brought about by the surcharge. A HEC-RAS plot of the immediately upstream cross-section and an X-Y-Z plot of the bridge and the upstream reach showing the backwater effects due to the drift accumulation are presented in Appendix C. Two standard tables from HEC-RAS are also presented with various hydraulic parameters from both the debris and non-debris conditions.

The DBP3 model also makes some hydraulic computations to simulate the effects of floating debris accumulations at bridge piers. Scour calculations are performed, based upon the Melville and Dongol method (1992). The necessary input variables for the scour calculations are those used for the probabilistic estimation of drift accumulation at a bridge (described above), plus velocity, sediment characteristics, and pier size, shape and alignment with flow. The values for the scour calculations were very roughly estimated, as floating debris-induced scour is generally outside the scope of this thesis. The hydrostatic pressure force normal to the bridge pier, due to the debris raft is reported to be 365 lbf per foot width (5.323 kilonewtons per meter width). The dynamic pressure force on the pier caused by the debris raft is 13,000 lbf (57.8 kilonewtons). Both of these values, though, are calculated using the estimated upstream velocity and flow depth that were entered to run the program. In order to calculate these values properly, the DBP3 program should either be run again or the values should be determined using the equations presented in the Literature Search.

Discussion of Results

The results of this example are only estimates intended for the demonstration of procedure. The numbers used should be noted on a relative basis for comparison. However, it is important to note that a relatively small drift accumulation caused a 2.3-foot increase in water surface elevation, whose effects extended for almost one mile upstream, and a 48% increase in local velocities, thus demonstrating that the hydraulic effects of floating debris accumulations may be hard to predict, but they are not negligible.

VI. Discussion, Conclusions, and Recommendations

Discussion of Findings

Over the past ten years, the scientific community has focused a significant amount of attention on the accumulation and effects of floating debris at bridges and culverts. Many qualitative and quantitative aspects must be taken into consideration in order to evaluate the effects of floating debris arriving at a bridge or a culvert. Literature indicates three major steps are common in the analysis of floating debris: 1) evaluation of the potential quantity of floating debris delivered to the bridge or culvert site, 2) approximation of the quantity of floating debris accumulating at the site, and 3) hydraulic representation of the site incorporating the potential floating debris accumulation.

The combination of qualitative and quantitative factors can greatly increase the understanding of the floating debris accumulation phenomenon. By applying the basic principles of hydraulic engineering and using models as tools to assist in comprehension, an understanding of the effects of floating debris accumulations at bridges and culverts can be achieved. The methods and models reviewed were the Diehl (1997) qualitative method of potential drift accumulation, the Debris at Bridge Pier Prediction Program (DBP3) (Wallerstein, 1999) for both quantification of potential drift accumulations and scour, and HEC-RAS (U.S. Army Corps of Engineers, 1998) for quantitative hydraulic values. A combination of the Diehl and DBP3 methods, including assessment of more site-particular characteristics, will enable proper evaluation of potential drift accumulation at a bridge or culvert.

By reviewing the comments from 27 responding state departments of transportation, a rough characterization of the status of floating debris at bridges and culverts can be drawn. A general consensus states that:

1. Floating debris can be a minor to moderate problem; however, it is not deemed to be a major problem (59% of respondents).

2. The percentage of the annual bridge and culvert maintenance budget allocated towards debris removal is most commonly unknown or not readily available (48% of respondents), or typically estimated as less than one percent (55% of respondents that estimated a percentage).

3. Deposited debris removal programs are handled on a case-by-case basis (89 % of respondents), where periodic bridge inspection teams indicate which bridges need debris removal and district maintenance forces or contractors then remove the obstructions (37 % of respondents). Several states investigate bridges that have a tendency to accumulate drift for floating debris blockages during, or immediately after, large storm events (19 % of respondents).

4. Along with floating debris-induced scour and increased loads on piers considerations that are dictated by AASHTO, providing a clear span to allow floating debris passage is the dominant consideration of floating debris in the hydraulic and structural design of bridges (48 % of respondents).

5. Preventative maintenance through debris removal at the structure and upstream of the site is the primary countermeasure that respondents found effective and cost efficient (26 % of respondents). However, many of respondents would not specify an effective or cost efficient floating debris countermeasure (30% of respondents).

By viewing these results, we can interpret a common opinion of state bridge engineers that the most efficient way to approach floating debris accumulations at bridges and culverts is to operate on a case-by-case basis at the local level. This approach, however, has led to a widespread failure to observe the costs associated with floating debris removal, repair of damages, and maintenance. Local site maintenance is implemented along with some general design concerns (such as in-water pier avoidance) in order to reduce the frequency of drift accumulations. Problematic bridges still do exist in most regions, but are largely considered an acceptable inconvenience, with few states implementing structural countermeasures to further protect these structures.

Conclusions

The adoption of a consistent protocol for the quantification of floating debris accumulations has been hampered by the many site dependent variables associated with floating debris accumulations and their hydraulic effects at bridges and culverts, but one should be undertaken in order to guide engineers and modelers in the consideration of drift in the design and analysis process of hydraulic structures. A recommended analysis protocol incorporating existing methods is presented. This thesis has cumulated in the realization of four major points:

1) Floating debris can be a significant and quantifiable factor in the hydraulic performance of bridges and culverts.

2) State bridge engineers view floating debris as a minor to moderate problem that is best addressed on a case-by-case basis on the local level by district maintenance forces.

3) The largely decentralized approach towards floating debris prevention and maintenance has resulted in a general unavailability of information regarding the costs of floating debris (i.e., damages and maintenance).

4) An analysis protocol considering both qualitative and quantitative factors is presented to evaluate the potential hydraulic effects of floating debris, implementing flowcharts and computer models to guide the process.

Recommendations for Further Work

As a recent development, two projects dealing with the accumulation of floating debris at bridges are currently being developed. The first is a USGS report authored by Timothy Diehl and is being published by the Federal Highway Administration (FHWA) (Diehl, 1999). This upcoming report will provide a statistical study of data relevant to debris accumulations, a detailed study of factors affecting drift accumulation at selected bridges, and the description of drift generation, transport and trapping in a study reach (Diehl, 1999). Another exciting development will be the National Cooperative Highway Research Program's (NCHRP) project titled "Design Specifications for Debris Forces on Highway Bridges", authored by Arthur Parola (National Cooperative Highway Research Program, 1999). This work will develop analytical methods to quantify impact, drag and hydrostatic forces on bridges due to drift accumulations. A simple procedure should be developed that will be used as the basis for specifications to calculate the floating debris-induced forces on bridges (National Cooperative Highway Research Program, 1999).

The evaluation of floating debris effects at bridges and culverts would greatly benefit from further investigation into the costs associated with drift-related damages, maintenance costs, and countermeasure costs. District bridge engineers and maintenance forces possess considerable knowledge as to the local occurrence of floating debris problems and, thus, should be consulted, if possible. A comparison of parameters (i.e., cost, efficiency, maintenance, etc) of various floating debris countermeasures at a single site, versus the no-action tactic, would be a useful tool illustrating the advantages and disadvantages associated with each approach. The development of design criteria and considerations for the selection of a floating debris countermeasure would greatly aid in the mitigation of floating debris-induced damages at problematic bridges.

Investigation into the size and type of floating debris on a regional basis will aid in the process of floating debris characterization throughout the country. Communication and proper documentation of regional floating debris characteristics will further the knowledge base for all involved with the hydraulics of floating debris.

Several municipalities and state departments of transportation have recently implemented the use of computer databases in the management of bridge and culvert maintenance. Often, these databases include fields documenting floating debris accumulations, damages, and costs. Soon, a significant amount of data will be available in these databases allowing historic evaluation of floating debris accumulations and damages at a bridge or culvert site.

References

References

Abt, S. R., T. E. Brisbane, D. M. Frick and C. A. McKnight (1992), "Trash Rack Blockage in Supercritical Flow", Journal of Hydraulic Engineering, ASCE, v. 118, no. 12, p. 1692-1696.

Abt, S. R., S. J. Dudley and J. C. Fischenich (1998), "Woody Debris Influence on Flow Resistance", Proceedings of the ASCE Wetlands Engineering Restoration Conference, ASCE.

American Association of State Highway and Transportation Officials (1997), "1997 Interim Revisions to the Standard Specifications for Highway Bridges", Sixteenth Edition.

American Association of State Highway and Transportation Officials (1998), "AASHTO LRFD Bridge Design Specifications – Customary U.S. Units", Second Edition.

American Society of Civil Engineers and Water Environment Federation (1992), "Design and Construction of Urban Stormwater Management Systems", ASCE Manuals and Reports of Engineering Practice No.77, WEF Manual of Practice FD-20.

Arkansas State Highway and Transportation Department (1999), "Bridge Closed in Madison County", News Release NR99-044, available at URL: *http://www.ahtd.state.ar.us/News/News1999/NR99-044.htm*

Arnoult, J. D. (1986), "Culvert Inspection Manual: Supplement to the Bridge Inspector's Bridge Manual", Federal Highway Administration, Report No. FHWA-IP-86-2.

Barnes, H. H. (1967), "Roughness Characteristics of Natural Channels", United States Department of the Interior, Geological Survey, Water Supply Paper 1849.

Burns, Rebecca (1999), Pennsylvania Department of Transportation, Bureau of Design - Bridge Quality Assurance Division, electronic correspondence on September 7 and 13, 1999.

Carleton, M. G., and J. S. Nielsen (1990), "A Study of Trash and Trash Interception Devices", Water Science and Technology, International Association on Water Pollution Research, v. 22, no. 10/11, p. 287-290.

Chang, F. F. M. (1973), "A statistical summary of the cause and cost of bridge failures", Federal Highway Administration, Office of Research and Development, Report No. FHWA-RD-75-87.

Chow, V. T. (1959), "Open Channel Hydraulics", McGraw-Hill, New York.

Diehl, T. H. (1999), "Debris Accumulation at Bridges", unpublished report, FHWA, U.S. Department of Transportation, available at URL: *http://tenn.er.usgs.gov/pubs/OFR97-113/a35.html*

Diehl, T. H. (1994), "Causes and effects of valley plugs in West Tennessee; responses to changing multiple-use demands", New Directions for Water Resources Planning and Management, American Water Resources Association, p. 97-100.

Diehl, T. H. (1997), "Potential drift accumulation at bridges", U.S. Federal Highway Administration Publication No. FHWA-RD-97-028, available at URL: *http://tn.water.usgs.gov/pubs/FHWA-RD-97-028/drfront1.htm*

Diehl, T. H., and B. A. Bryan (1993), "Supply of large woody debris in a stream channel", *in* Shen, H.W., Su, S.T., and Wen, Feng, eds., Hydraulic engineering '93 conference, San Francisco, 1993, Proceedings: American Society of Civil Engineers, v. 1, p. 1055-1060.

Gurnell, A. (1997), " The Hydrological and Geomorphological Significance of Forested Floodplains", Global Ecology and Biogeography Letters, v. 6, no. 3-4, p. 219-229, University of Birmingham, School of Geography.

Hagerman, David (1999), City of Knoxville, Department of Engineering and Public Works, electronic correspondence on November 4, 1999.

Hamilton, D. L., R. C. MacArthur and V. A. Vanoni (1994), "Modelling of Flood Propagation over Initially Dry Areas", Specialty Conference on Modelling of Flood Propagation Over Initially Dry Areas Proceedings, ASCE, Milan, Italy, p. 342-356.

Kansas State Department of Transportation (1999), "Design Manual", Vol. 3, Version 7/99, Bridge Section, p. 209-210.

Martin, S. K. (1989), "Clover Fork Diversion Project, Harlan, Kentucky: Hydraulic Model Investigation", Department of the Army, Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, Technical Report HL-89-18.

McEnroe, B. M., and L. M. Johnson (1995), "Hydraulics of Flared-End Sections for Pipe Culverts", Transportation Research Record, Is. 1483, p. 72-79.

McFadden, T., and M. Stallion (1976), "Debris of the Chena River", ADA-029 357, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.

Melville, B. W., and D. M. Dongol (1992), "Bridge Pier Scour with Debris Accumulation", Journal of Hydraulic Engineering, ASCE, v. 118, no. 9, p. 1306-1310.

Mueller, D. S. and A. C. Parola (1998), "Detailed Scour Measurements around a Debris Accumulation", International Water Resources Engineering Conference Proceedings, ASCE, Reston, VA. USA, v. 1 1998, p. 234-239.

National Cooperative Highway Research Program (1999), "National Cooperative Highway Research Program – Active Project", available at URL *http://www4.nas.edu/trb/crp.nsf/All+Projects/NCHRP+12-39*

National Transportation Safety Board (1990), "Collapse of the Harrisson Road Bridge Spans Miamitown, Ohio May 26, 1989", HAR-90-03, Washington, D.C., National Transportation Safety Board.

Normann, J. M., R. J. Houghtalen and W. J. Johnson (1985), "Hydraulic Design of Highway Culverts", Hydraulic Design Series No. 5, Report FHWA-IP-85-15, FHWA, U.S. Department of Transportation.

Ogden Environmental and Energy Services, Inc. (1999), "Ten Mile Creek Watershed Flood Study", Draft Report, *prepared for* Knox County Engineering and Public Works.

Parola, A. C., T. E. Fenske and D. J. Hagerty (1994), "Impacts of 1993 Upper Mississippi River Basin Floods on Highway Systems", Transportation Research Record, Is. 1483, p. 32-37.

Perham, R. E., (1988) "Elements of Floating-Debris Control Systems", Tech. Report REMR-HY-3, U.S. Army Cold Regions Research and Engineering Lab., Hanover, NH.

Perham, R. E., (1987) "Floating-Debris Control: A Literature Review", Tech. Report REMR-HY-2, U.S. Army Cold Regions Research and Engineering Lab., Hanover, NH.

Reihsen, G., and L. J. Harrison (1971), "Debris-Control Structures", Hydraulic Engineering Circular No. 9, FHWA, U.S. Department of Transportation.

Sadler, J. F. (1999), "Talking Trash II: A Return to Debris Removal", Proceedings from the Ninth Annual Tennessee Water Resources Symposium, Nashville, TN, working paper

Shields, F. D., Jr., and C. J. Gippel (1995), "Prediction of effects of woody debris removal on flow resistance", Journal of Hydraulic Engineering, v. 121, no. 4, p. 341-354.

Smith, J. P., and M. W. Collopy (1998), "Regional trends of biological resources--Pacific Northwest", Pages 645-705 in M. J. Mac, P. A. Opler, C.E. Haecker, and P. Doran, editors. "Status and trends of the nation's biological resources", Vol. 2., U.S. Department of the Interior, U.S. Geological Survey, Reston, Va., available at URL: *http://biology.usgs.gov/s+t/SNT/noframe/pn169.htm*

Swann, A. A. (1999), M.Sc. Thesis, "Floating Debris on Lakes and Rivers: Effects on Operation, Use, and Safety of Lakes and Dams", University of Tennessee, Knoxville, TN.

Tennessee Department of Transportation (1998), "Tennessee Hydraulic Memoranda", Structures Division, available at URL: *http://www.state.tn.us/transport/index.html.*

Tschantz, B. A., B. J. Frederick, and W. A. Miller (1999), "Laboratory Manual for the CE 390 Hydraulics Laboratory", University of Tennessee, Civil and Environmental Engineering Department, Knoxville, TN.

US Army Corps of Engineers (1998), "HEC-RAS River Analysis System: Hydraulic Reference Manual", Version 2.2.

Wallerstein N. (1999), "Debris at Bridge Pier Prediction Program (DBP3) User Manual", University of Nottingham, Department of Geography.

Wallerstein N., C. R. Thorne and M. W. Doyle (1999), "Spatial Distribution and Impact of Large Woody Debris in Northern Mississippi", University of Nottingham, Department of Geography, working paper.

Wallerstein, N., C. R. Thorne and S. R. Abt (1996a), "Debris Control at Hydraulic Structures Contract Modification: Management of Woody Debris in Natural Channels and at Hydraulic Structures", US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Wallerstein N., C. R. Thorne and S. R. Abt (1996b), "Debris Control at Hydraulic Structures in Selected Areas of the United States and Europe", US Army Research, Development and Standardization Group-UK, U.S. Department of Defense.

Washington State Department of Transportation (1997), "Hydraulics Manual", Environmental and Engineering Service Center, Hydraulics Branch, Engineering Publication M23-03, available at URL: *http://www.wsdot.wa.gov/fasc/EngineeringPublications/library.htm*

Appendices

Appendix A

Responses to the Survey of State Bridge Engineers

Title **Page**

Name of Survey Respondent:
Title:
Organization:

University of Tennessee Survey:

Effects of Floating Debris at Bridges and Culverts *8/99*

1. Is floating debris and its associated blockages at bridges and culverts a major problem in your state?

   Comments:

2. What is the annual budget for maintenance of bridges and culverts under your jurisdiction? Approximately what percentage is allocated for debris removal and repairing debris-related damages?

   Comments:

3. Describe your organization's maintenance program to remove debris from bridges and culverts (i.e., periodic or case-by-case, etc.). Please elaborate and/or send a copy of the maintenance program.

4. Do you consider floating-debris in the structural or hydraulic design and analysis of bridges and culverts? How? (i.e., trash racks, extra wide spans, pier shape and type, etc.)

5. What type of floating-debris countermeasure do you find most effective and cost efficient? (i.e., bank clearing maintenance, skimmer booms, trash racks, clear cutting regulations, trash education/awareness programs, etc.)

Please send any written guidelines, policy programs, and design standards relating to floating debris accumulation at bridges and culverts. All additional information will be greatly appreciated.

Please return this survey to:

Thomas G. Mihlbachler
Department of Civil and Environmental Engineering
University of Tennessee
223 Perkins Hall
Knoxville, TN 37996-2010

Tel: 423 637 8821
Fax: 423 974 2669
email: tmihlbac@utk.edu

Is floating debris and its associated blockages at bridges and culverts a major problem in your state?

AK	It's a problem - depends how you define major.
AR	Based on comments from the District Maintenance Engineer/Superintendent, drift seems to be a minor concern. See the attached files for District responses to questions 1, 2, & 3.
AR10	We do not consider this work to be a major problem. We have 2 cranes/draglines that enable us to pull drift effectively.
AR2	No, most problems with drift accumulating on state maintained bridges are in the delta sections of District 2. Primarily in Desha, Chicot, and Ashley counties.
AR3	No
AR6	No. Last year only $56.01 was charged to Channel Work/Drift Removal. I'm sure more was actually done but was charged to a ditch related function. Drift/debris removal is primarily of sedimentation or vegetation at culverts. In eleven years there has not been an instance of a large log jam on a major stream crossing.
AR7	Generally speaking it is not a major problem. We did however have to close a bridge this past winter because a large tree floating down the channel hit and broke 2 timber piles from a 3 pile bent under a bridge in Clark County. It took approximately 1 week to make the needed repairs. We seem to have to do more of this type work as the timber industry is increasing the amount of timber cutting they do.
AR9	No.
AZ	It is not a major problem. However, we do have a debris problem at some bridges and culverts.
CT	It is not a major problem. We have noticed an increase in the amount of accumulated sands in multi-cell culverts recently installed. We attribute this to lower velocities as a result of the increased hydraulic opening.
GA	This is a moderate problem in Georgia, usually attended to by our maintenance forces.
IN	I am not sure it is a major problem. It varies from District to District and annual rainfall or intensity of the rainfall at wooded locations.
KS	Can be a problem if allowed to accumulate.
KY	Yes, in some cases. It can nearly block the opening or cause pier undermining.
MA	The State completed its Scour Critical Bridge Program on 2357 bridges in the State. Of those 2357 bridges 526 are categorized with a high potential for debris accumulation.
MD	no.
MI	No

Is floating debris and its associated blockages at bridges and culverts a major problem in your state? (continued)

MN	Yes, but major problems are associated with major floods. Debris accumulations during non-flooding are removed by maintenance forces and are a minor problem.
MS	Yes. It collects on bridge bents, obstructs the flow of streams and has the potential for undermining bridge foundations.
MT	Moderate problem.
ND	Can be a problem in some areas of the State, but is not a major problem in North Dakota.
NH	Minor problem. We routinely address debris & remove it.
NJ	Very few local bridges have inadequate waterway opening that may cause blockages at bridges due to floating debris. None of the bridges on the State highway system have any major problem
OH	A real problem, but not extremely wide spread.
OK	Yes, this is problem becomes much more apparent after a major flood.
OR	Yes. It would appear that the volume has been rather dependent on the logging activity in a given watershed, as well as , the frequency of major run-off water events, and the number of in-water bents.
PA	Our Bridge Management System (BMS) indicates 6400 bridges, or approximately 26% of PennDOTs bridges over 8' have a need for debris/vegetation removal. The BMS system does not differentiate between floating debris and vegetation removal. For example, these numbers may indicate shrubs on an adjacent gravel bar or under the bridge, which may need to be removed, or they may indicate debris lodged on pier tops or abutments. Generally, however, we would not classify debris as a major problem unless the bridge was suddenly closed to high traffic volumes. We do not track whether or not debris is the determinative factor in our flood-related closures. Anecdotally, we have heard debris is a contributing factor on some of these bridges, but do not have hard facts to quantify this.
TN	I wouldn't consider it major, however it is a problem, especially in erodible soil.
TX	Yes, because it causes lateral forces on the vertical members of the structure during high flow situations. It is also a major factor in producing localized and contraction scouring.
UT	Southern portion of the state on streams that support Tamarisk i.e., Salt Cedar trees only.
VA	It does occur from time to time.
VT	Yes.
WY	It is a problem, but not a major one. Several locations are problem sites.

What is the annual budget for maintenance of bridges and culverts under your jurisdiction? Approximately what percentage is allocated for debris removal and repairing debris-related damages?

AK	Annual Maintenance Budget: $5000,000. 10% spent on debris removal & repair related damage.
AR	From information supplied by Pat Sullivan, Staff Maintenance Engineer, the state bridge maintenance budget for the current fiscal year is $5,200,000 with $294,000 allocated to Channel Work/Drift Removal. Drift removal at culverts is not a separate budget item, but would be part of ditch maintenance. The current annual amount budgeted for ditch maintenance is $6,800,000; the cost of removing floating debris from culverts is not separated from that, but would be a fairly small percentage. It may be an insignificant portion of the cost of maintaining ditches. Based on the bridge maintenance budget alone, drift removal and associated repairs amounts to 5.7% of the state bridge maintenance budget. See the attached District comments.
AR10	We do not budget specifically for this work. The following are 494 function(channel work/drift removal) expenditures for FY 1999: Payroll(inc. additives)$32666.82; Equip. rental $21935.12; Total $54601.94 Our 494 function expenditures for last year do not indicate any expenses for repairs, so the drift did not cause any damage.
AR2	There is not an annual allotment set side solely for maintenance of bridges and culverts. However District 2 budget for '98 - '99 was allotted: Salaries - $5,462,100; Payroll additives - $150,000; Equipment - $3,511,680; Totals - $9,123,780; Charges made to function #494 (Channel Work/Drift Removal) in District 2 for '98 -'99 was: Salaries - $9,815.70; Payroll additives - $5,638.48; Equipment - $8,558.08; Totals - $24,012.26; Amount spent on function #494 compared to the total annual allotment was only 0.2632% of District 2 '98 - '99 budget.
AR3	$300,000 of Expense Allotment - Does not include labor or equipment. 5% for Debris Removal
AR6	There is not a separate budget for bridge maintenance. Debris removal is a very very small part of the district expense budget.
AR7	Last Fiscal Year we had 1535 man hours of channel work/drift removal. The plan total for this function in our Maintenance Management Program was 1240 man hours. As mentioned above the more timber is cut it seems like the more drift we have to remove from our drainage structures. Pat Sullivan (Maintenance Division) is the best source of information on this question.
AR9	No budgeted amount or percentage.
AZ	Minor maintenance work is carried out by our District Maintenance organizations through their budget. The debris removal is considered as minor maintenance work.
CT	Our total bridge maintenance budget is $7,000,000 for 6000 bridges. Less than 1% of that is spent on debris removal.
GA	$15, 000,000 estimated ; $5000/yr estimated

What is the annual budget for maintenance of bridges and culverts under your jurisdiction? Approximately what percentage is allocated for debris removal and repairing debris-related damages?(continued)

IN	It varies from District to District. Southern Districts have more problems with debris than Northern Districts. Southern Districts have annual budget for debris removal ranging from $100,000 to $150,000, while other Districts may have debris removal once every other year.
KS	Contract Bridge Maintenance is rarely utilized for drift removal. Drift removal is typically performed by state maintenance personnel, therefore that expenditure is not readily available.
KY	About $10,000,000 for contract maintenance of about 9,000 bridges. Possibly about $12,000,000 for routine maintenance by district personnel.
MA	The budget for maintenance of Massachusetts's bridges is state funded only. The Department's Maintenance Division uses these funds as required under a prioritization program. The removal of debris at bridges and culverts is not reserved as a percent of this budget.
MI	Contact Sonja Spitzley, Finance 517 335 2258
MN	There is no specific amount budgeted; however about $3-4 M is spent annually on bridge maintenance by State crews. We cannot determine the amount spent on debris removal but it is not a large percentage in a normal year.
MS	That data is not maintained by this office.
MT	$1.6 M overall, don't know breakdown for debris related maintenance.
ND	About $450,000; None is specifically for debris problems.
NH	$6,000,000 annual budget; $50,000 removal of debris
NJ	Approximately $ 7.0 M. There is no specific amount allocated for debris removal.
OH	Debris is removed usually after it has really plugged up an opening.
OK	Budget is not allocated by line items.
OR	The bridge maintenance crews, in the state of Oregon, are directed by a geographic located District Manager and do not report directly to the Bridge Section. Therefore without extensive research exact budgetary figures are unavailable. On average each of our 15 bridge maintenance and drawbridge crews have an annual budget of approximately $300,000. Of that budget, only about 5-10% is allocated towards drift & debris removal.
TN	For Contract Maintenance of bridges on State & Federal roads $30-35 M. Debris removal etc., is commonly handled by Regional Personnel. You can contact each Regional bridge engineer.
TX	The annual budget for FY 1999 was 18,000,000. Approximately 30% of that was for bridge channel and under bridge maintenance.
UT	Don't know.

What is the annual budget for maintenance of bridges and culverts under your jurisdiction? Approximately what percentage is allocated for debris removal and repairing debris-related damages?(continued)

VA	N/A, unknown.
VT	Bridges $1,000,000. Culverts $2,125,000. Less than 1% used for debris removal.
WY	Maintenance budget is administered by the 5 districts with no formal allocation for bridge and culvert maintenance. Most debris removal is accomplished by State Maintenance forces.

Describe your organization's maintenance program to remove debris from bridges and culverts (i.e., periodic or case-by-case, etc.).

AK	Case-by-case.
AR	See attached District comments.
AR10	It is handled on a case by case basis.
AR2	As drift accumulates, most times only after locally heavy rains events, Area Maint. Supervisors, Dist. Bridge Inspector, and Dist. Bridge Superintendent check for drift and debris build-up. Debris removal is assigned to the District Bridge Crew. Work is schedule most times during high water using a motor crane with clam-bucket to remove material from the area up stream side of the structure.
AR3	Case by Case. The Area Supervisor keeps a check on drainage structures and removes debris as it develops.
AR6	Debris removal is usually scheduled as the result of routine bridge inspections or observation by Area Maintenance Supervisors. If a debris problem is indicated on a Bridge Inspection Form V the data is entered into the Form V database then the form is distributed to the appropriate Area Supervisor for action. Once the debris is removed that information and the date it was removed is entered on the form and it is returned to the District Maintenance Engineer who enters this information into the Form V database and returns the form to the bridge inspector for his records.
AR7	We schedule periodic debris removal unless an emergency arises. We review bridge inspection reports and our Bridge Supervisor monitors structures to determine when work is required. We do more of this type work when it is dryer when we can do a better job of it. We just purchased a new trackhoe and we expect to utilize it in this work to a great extent.
AR9	Case by case as needed.
AZ	The District Maintenance organizations remove debris on case-by-case basis on the recommendations of our Bridge Inspection teams.
CT	We handle blockages on a case-by-case basis. Problems are reported to us by our Bridge Safety Department, maintenance staff, Town engineers, and our hydraulics and drainage section.
GA	This is done on a case-by-case basis. Identified by bridge inspection personnel with work performed by District Maintenance personnel.
IN	Debris removal are done through contracts, it is administered by each District and depends on their needs. Usually it is done District wide to remove debris at different locations in the same contract
KS	Case-by-case as found by bridge inspectors. State maintenance forces remove what they can, however, deck maintenance is mostly what gets accomplished.
KY	District or county crews use devices such as clam buckets to remove and haul away. It is handled on a county-by-county basis.
MA	The Underwater Operations Unit of the Bridge Inspection Program does the removal of debris at bridges and culverts. Once the divers remove the obstruction the District Maintenance Division

Describe your organization's maintenance program to remove debris from bridges and culverts (i.e., periodic or case-by-case, etc.) (continued)

	supplies equipment and personnel to dispose of the materials. The bridge sites that are high debris sites are programmed by the Underwater Operations Unit to have routine inspections during the spring and scour inspections after major storm events.
MD	Removal of debris is performed by the districts on an as needed basis since debris accumulation can increase the impact of scour (sediment transport) and decrease waterway openings.
MI	Case-by-case. Biannual inspection determines/identifies need.
MN	Most debris removal would be late spring or summer following spring high water. Reviews by Maintenance personnel assigned to bridge maintenance would identify the need and removal would follow. This is routine as is spring cleanup for bridges with decks.
MS	On a case-by-case basis as needed.
MT	Case by case
ND	Our district offices are responsible for routine maintenance of bridges.
NH	During our annual washing & oiling of structures they are inspected by Bridge Maintenance crews for debris (in addition to normal bridge inspections).
NJ	There is no specific program. It is based on if and where needed.
OH	Case-by-case basis. Debris removal is near the bottom of the list because it is very difficult to remove.
OK	Case-by-case. Priority determined by restriction of flow and increased scour.
OR	Usually our drift / debris removal is on a case by case basis, because it's so sporadic. However, during a high water event, we do know specifically which structures tend to collect more debris than others, and which structures have been determined to be scour critical.
TN	Each of the four Regional bridge engineers has two bridge repair teams that perform some repairs and light maintenance on bridges. These crews remove debris on an as need basis.
TX	Removal of debris is on a case-by-case basis. These bridges are periodically inspected and if debris is present then it is removed.
UT	Each maintenance shed foreman schedules maintenance activities like this on a case-by-case basis.
VA	Case by case
VT	On a case-by-case basis.
WY	See above responses.

Do you consider floating-debris in the structural or hydraulic design and analysis of bridges and culverts? How? (i.e., trash racks, extra wide spans, pier shape and type, etc.)

AK	Yes, span length greater than debris length, pier loading, scour, etc.... culverts will sometimes require a trash rack.
AR	Several features of structural design directly address drift accumulation. Freeboard between the design year flood water surface and the low chord of the bridge superstructure is provided (varies from one to two feet depending on location and type of road). We avoid placing bridge piers/bents in the center portion of a stream. We avoid using pier types that will encourage drift collection when our records indicate the presence of significant drift.
AZ	Floating debris is considered in the structural analysis of bridges and culverts by increasing the width of the pier.
CT	Floating debris and blockages are not considered in the design of bridges or culverts. They are considered for inlets of drainage basins, with a 50% blockage factor.
GA	No, not generally. We do provide wider spans over the channel and align the piers with the channel to minimize debris accumulation.
IN	Yes, by minimizing the number of piers in the water. Also, rounded pier nose.
KS	See Kansas State Bridge Manual pg. 3-221.
KY	We use a long bridge span as structurally feasible. We use baffle walls for multi-cell boxes to keep the flow and debris concentrated in one cell for the low flows.
MA	At high debris potential bridge sites, debris is considered in the scour analysis for the bridge as required by AASHTO. The Department does consider wider spans, pier shape, and pier and abutment alignment in the bridge design to prevent debris accumulation.
MD	The design of bridges and culverts are based on the latest AASHTO guidelines, which take into account foundation and scour concerns.
MI	Hydraulic - No; Structural - Underclearance 1' above 100-yr flood elevation. Pier shape for ice.
MN	Although we don't specially design for debris, we do design for ice loads which provides reserve structural strength to help resist debris loads (See #5).
MS	Yes, all of these.
MT	Case by case
ND	We try to allow freeboard on bridges for debris and/or ice. Also, we consider wider barrels on box culverts.
NH	Yes, pier reduction & longer spans.
NJ	None.

Do you consider floating-debris in the structural or hydraulic design and analysis of bridges and culverts? How? (i.e., trash racks, extra wide spans, pier shape and type, etc.) (continued)

OH	Not really, although longer spans and rounded pier shapes are used. We find that capped multiple pile piers do not seem to worsen debris collection.
OK	Yes, we will try to span the main channel with a single span when it is practical, or minimize the number of piers in the channel.
OR	Yes. If at all possible, minimize having any in-water substructure. If an in-water bent is required, consider substructure type and possible protective measures, such as trash racks or fender systems.
PA	We have used trash racks on some culverts with known or expected debris problems. Additionally, we generally try to maximize span lengths for reasons including environmental impacts as well as debris. Our AASHTO design specs (both Standard Specs 3.18.1.3 and LRFD Specs 3.7.3.1) include a broad direction to consider debris or drift loading, but no solid methodology. NCHRP 12-39 is attempting to develop more specific guidelines for our designers. Lastly, some of our older structures are equipped with armored pointed nose piers which were presumably for breaking up ice, but may be effective on debris rafts as well.
TN	Yes, extra wide spans, pier type and orientation. Also consider structure type, i.e. even though a reinforced concrete box bridge is acceptable hydraulically, we may opt for a girder bridge for greater horizontal clearance. Also pier placement is considered.
TX	No.
UT	Tamarisk invasion (non-native species) has developed remarkably over the last several decades and is only now recognized for its hydraulic hazards at structures.
VA	No
VT	Bridges - allow 1' of freeboard at design flow for ice and debris passage. Culverts - occasionally oversize by +/- 20% at high debris load locations. Also use debris racks in some locations.
WY	Yes, span ratios, pier shape, debris deflectors.

What type of floating-debris countermeasure do you find most effective and cost efficient? (i.e., bank clearing maintenance, skimmer booms, trash racks, clear cutting regulations, trash education/awareness programs, etc.)

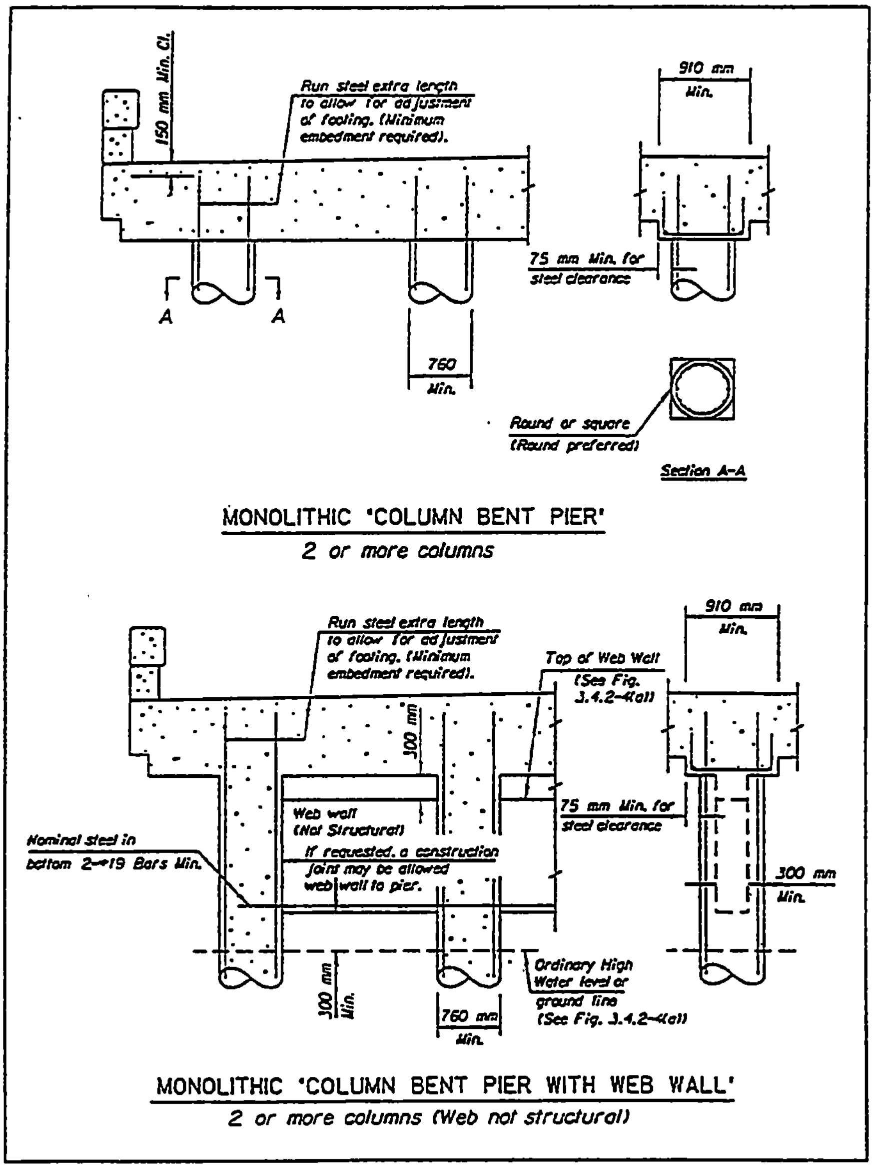
AK	Most of our debris problems are from bank instabilities well upstream of the structures. Other than routine maintenance at the structure, no other countermeasures seems effective or cost effective.
AR	Preventive maintenance (routine or case-by-case drift removal) has been our primary approach to handling this problem. We are currently developing plans for Job 009863 to replace one bridge that collapsed this Spring due to scour caused by drift. We are also currently placing riprap under another bridge (Job 100465) that was developing deep scour which was caused in part by drift.
AZ	We do not have any specific floating debris countermeasures. The debris is removed on case-by-case basis when it occurs.
CT	We find the best countermeasure is preventative maintenance. We remove debris, sand, and clear banks before a major problem is created.
GA	None.
IN	No countermeasure has been installed for this purpose. Some districts have annual debris removal contracts.
KS	Concrete web wall keeps trash from hanging up on columns or piling (See attached sheets 3-209 & 210).
KY	We have not done many countermeasures. We mostly clean up as funding allows.
MA	The department can not respond to this question, because a comparison of installed debris countermeasures has not been studied. Our response to this question would be purely speculative.
MD	The State Highway Administration (SHA) had traditionally USED SCS TR-20 for hydrologic modeling, which is, by nature, conservative, and leads to the design of oversize waterway structures. This has lead to a decrease in the overall concern for the impact of debris on flow through these structures. The SHA is required, by state law, to design for Ultimate Development, based on Zoning Maps for future development. This conservative procedure requires the State of Maryland to oversize its waterway structures, which allows it to compensate for losses in flows due to debris accumulation.
MI	N/A
MN	The only countermeasure used is pier shape and type. This is considered to be effective for bridges, but is limited in effectiveness as the problem is reduced but not eliminated.
MS	Brush deflector at the bent.
MT	Limited use of countermeasures. Resource Agencies would go ballistic if we even suggested bank clearing maintenance
ND	Same response as question 4.

What type of floating-debris countermeasure do you find most effective and cost efficient? (i.e., bank clearing maintenance, skimmer booms, trash racks, clear cutting regulations, trash education/awareness programs, etc.) (continued)

NH	Annual inspections & inspections after major flows in suspect areas.
NJ	Maintenance does not have any specific type of floating debris countermeasures in place. Cleaning up of debris is done as needed.
OH	We only have a few trash racks, and in my 15 years have never seen one designed or built.
OK	None.
OR	The only options we have available are not locating a bent in-water and the placement of protective measures like trash racks and fender systems. Controlling debris & debris removal have high political impacts in streams that support migratory fish habitat.
PA	We have not measured the cost effectiveness of our countermeasures we specify in design. Our inspectors bring debris problems to the attention of the design and maintenance staff. Trash racks are an acceptable method to prevent problems in culverts, but they also create additional maintenance work of removing debris from the rack on a periodic basis.
TN	1. Clear cutting regulations. 2 Longer spans over river channel (minimize obstructions) 3 Preventative measures for bank erosion upstream of bridges. TN Attached is the TN Dept. of Environment and Conservation's General Permit for debris removal. This permit will apply to all activities related to debris removal across the state. This permit is enforced by the Water Quality Section within TDEC.
TX	Bank clearing maintenance.
UT	Periodic removal of debris from piers, etc. The hazard is greatest in southern third of the state.
VA	None of the above are effective or efficient i.e., this is not a one-time solution.
VT	Trash racks, bank clearing maintenance. Clear cutting is not permitted by agency of Natural Resources.

Kansas Department of Transportation *Design Manual*

Column Bent Pier with Web Wall



Volume III
Version 7/99

BridgeSection

Figure A1 – Column Bent Pier with Web Wall (from Kansas Department of Transportation, 1999)

Web Wall Elevation

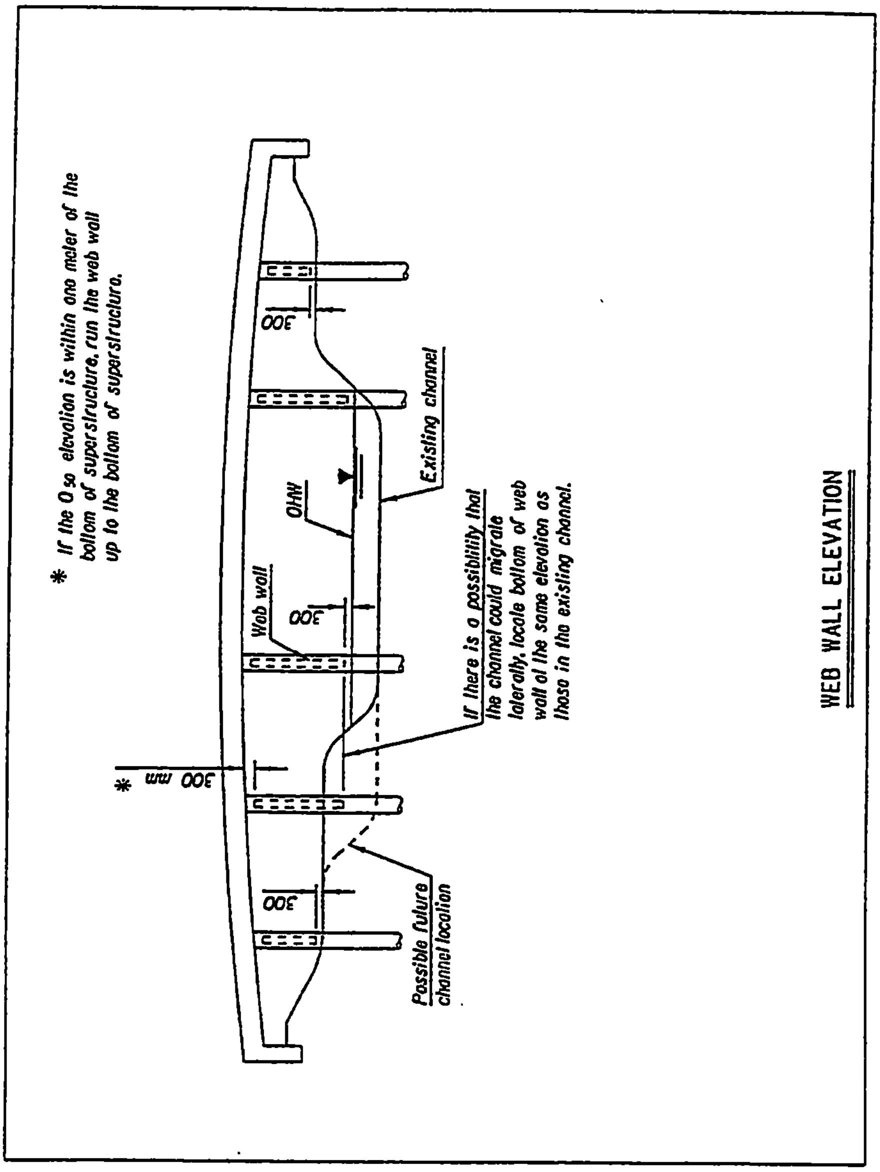


Figure A2 –Web Wall Elevation,(from Kansas Department of Transportation, 1999)

Appendix B

Flow Charts for the Diehl Method of Estimating Potential Drift Accumulation at Bridges

Title **Page**

Please note that all flow charts contained in this appendix are reprinted from:

Diehl, T. H. (1997), "Potential drift accumulation at bridges", U.S. Federal Highway Administration, Publication No. FHWA-RD-97-028, available at URL: http://tn.water.usgs.gov/pubs/FHWA-RD-97-028/drfront1.htm

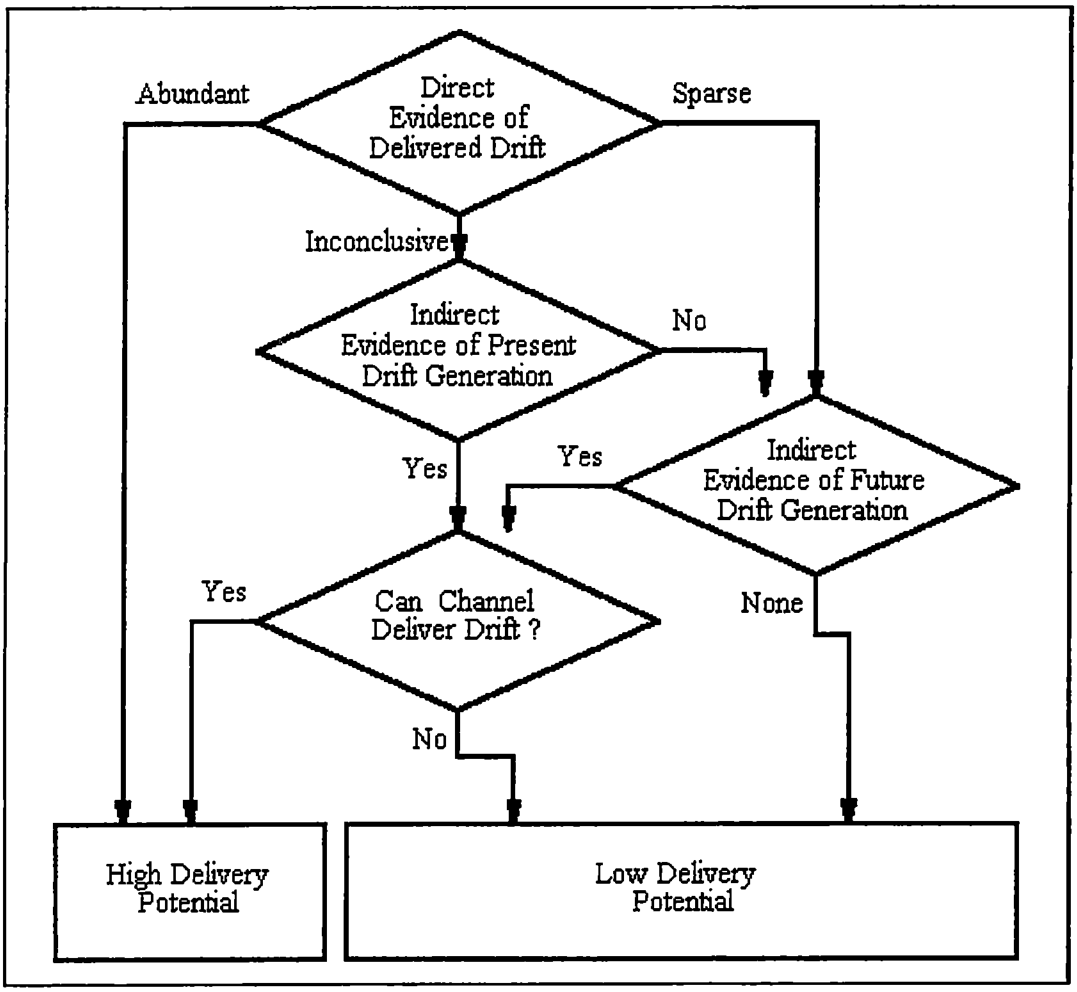


Figure B1 – Flow chart for evaluating potential for drift delivery.(from Diehl, 1997)

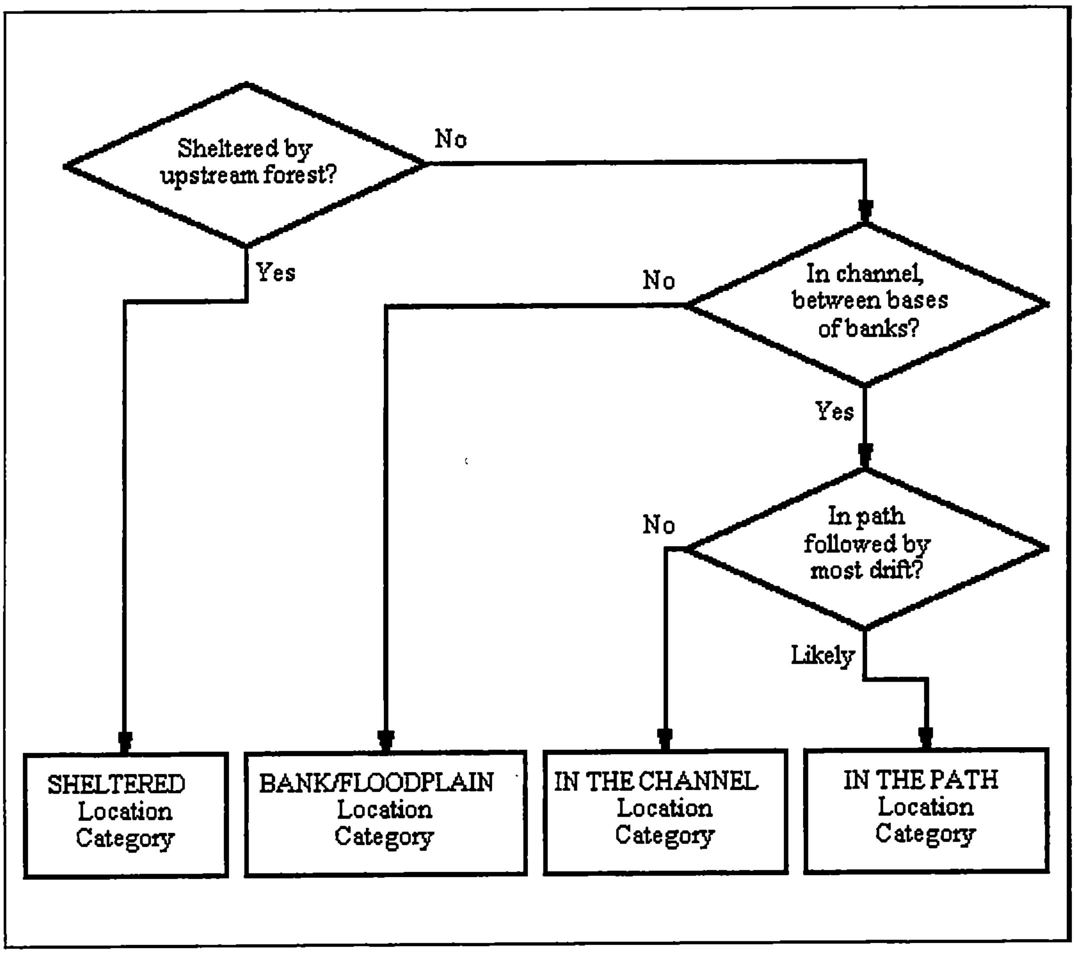


Figure B2 – Flow chart for determining location category.(from Diehl, 1997)

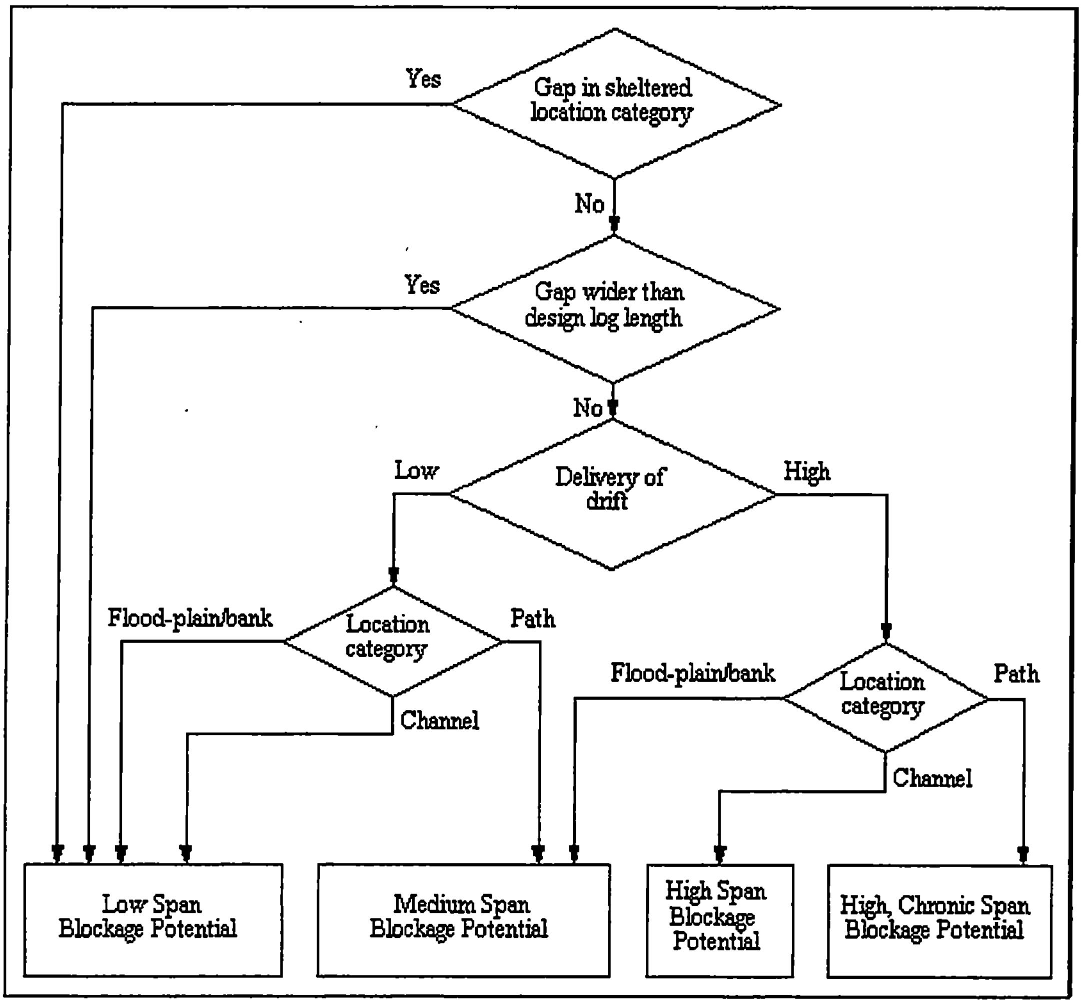


Figure B3 – Flow chart for determining potential for drift accumulation across a bridge span or vertical gap. (from Diehl, 1997)

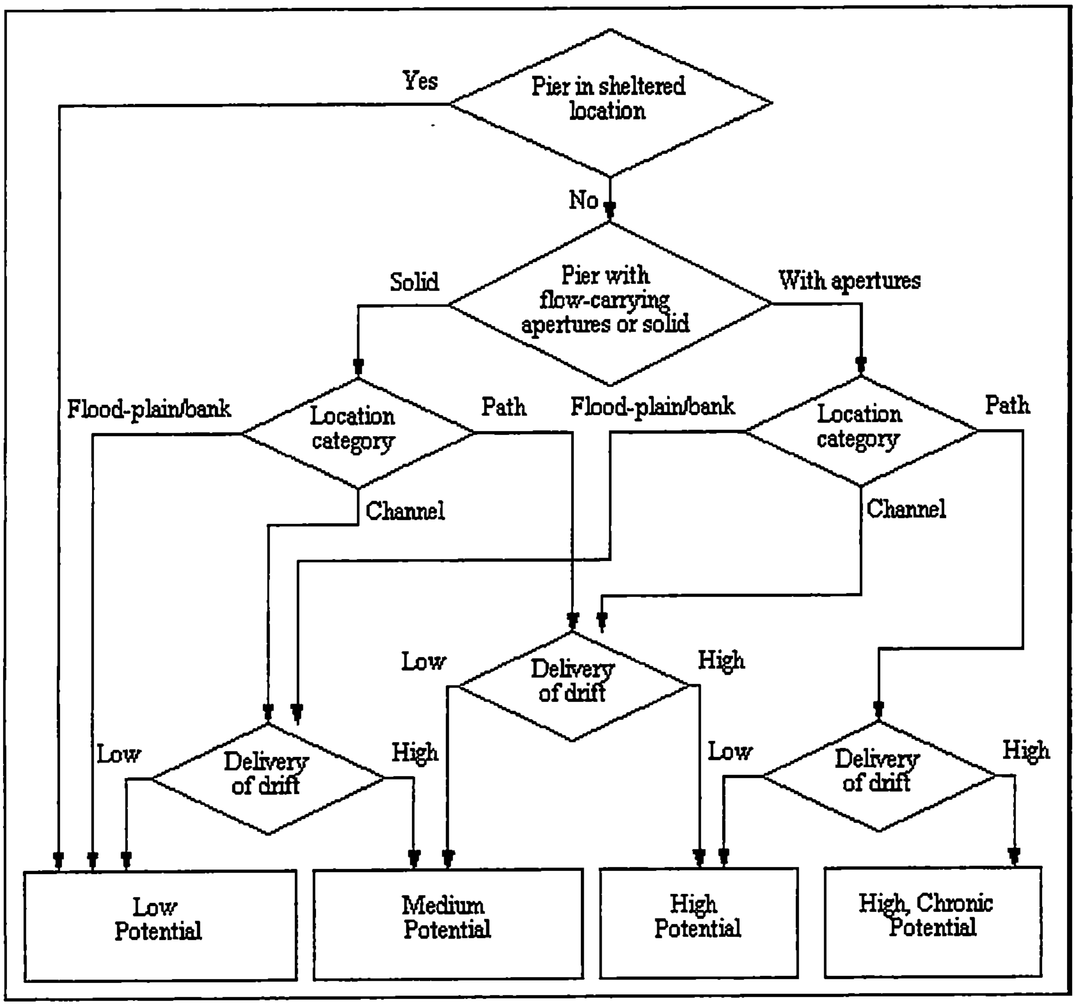


Figure B4 – Flow chart for determining potential for drift accumulation on a single pier. (from Diehl, 1997)

Appendix C

Ten Mile Creek Example Floating Debris Analysis

Please note that all flow charts contained in this appendix are adopted from:

Diehl, T. H. (1997), "Potential drift accumulation at bridges", U.S. Federal Highway Administration, Publication No. FHWA-RD-97-028, available at URL: http://tn.water.usgs.gov/pubs/FHWA-RD-97-028/drfront1.htm

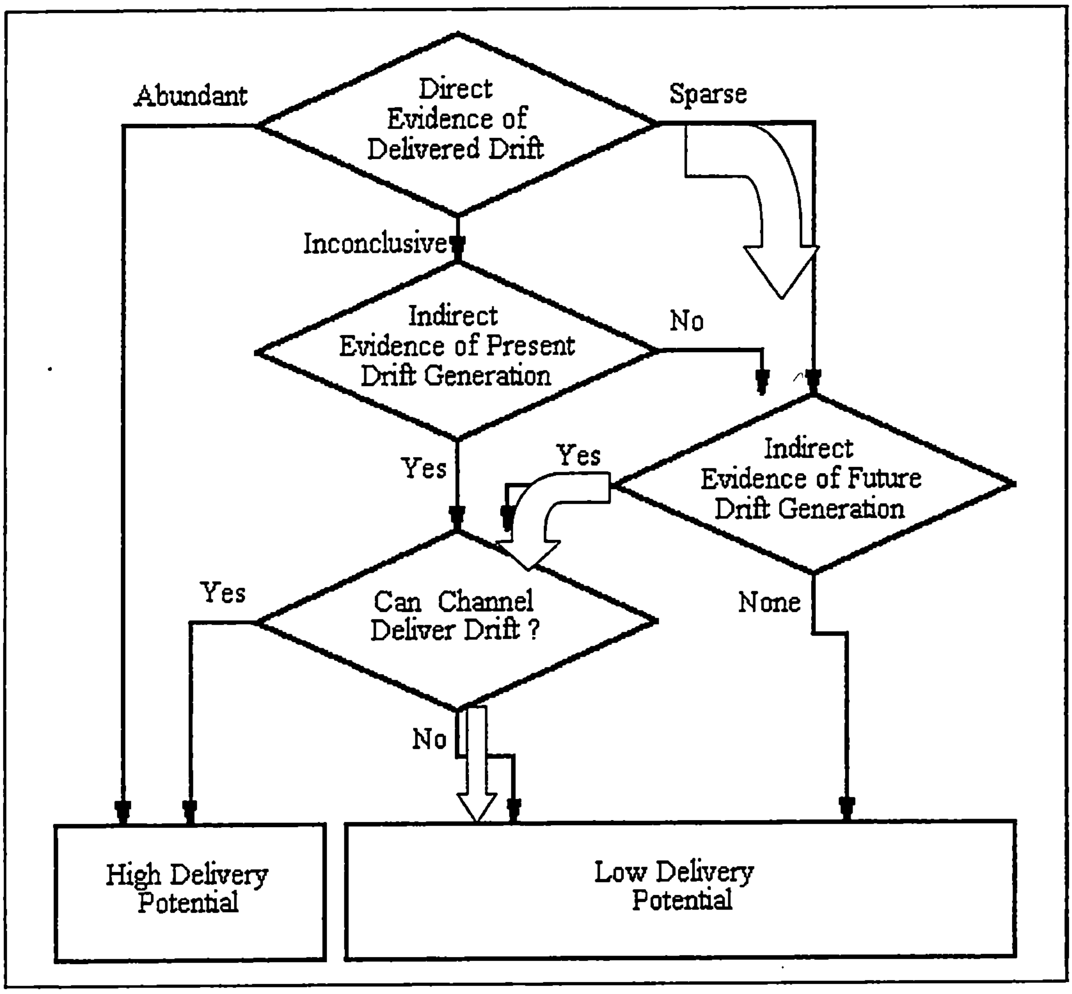


Figure C1 – Flow chart for evaluating potential for drift delivery, (from Diehl, 1997)

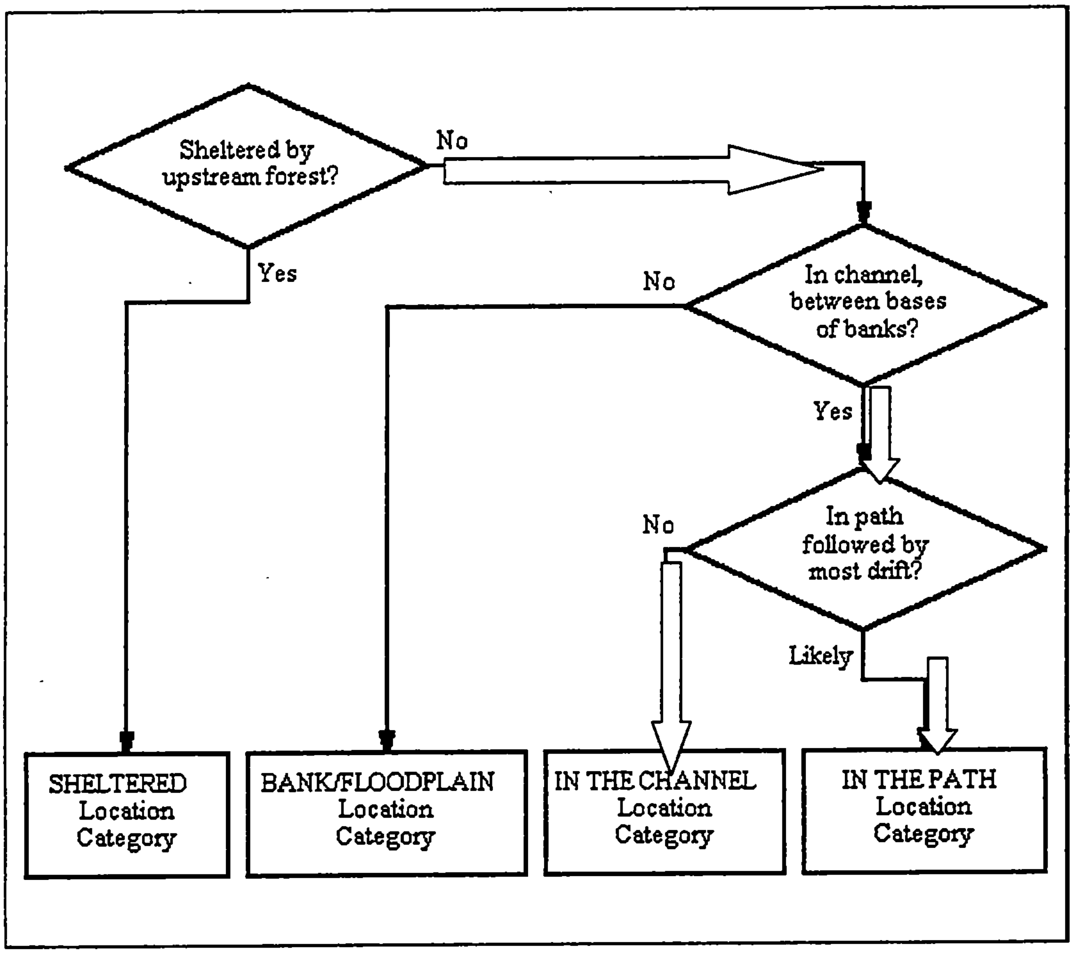


Figure C2 – Flow chart for determining location category.(from Diehl, 1997)

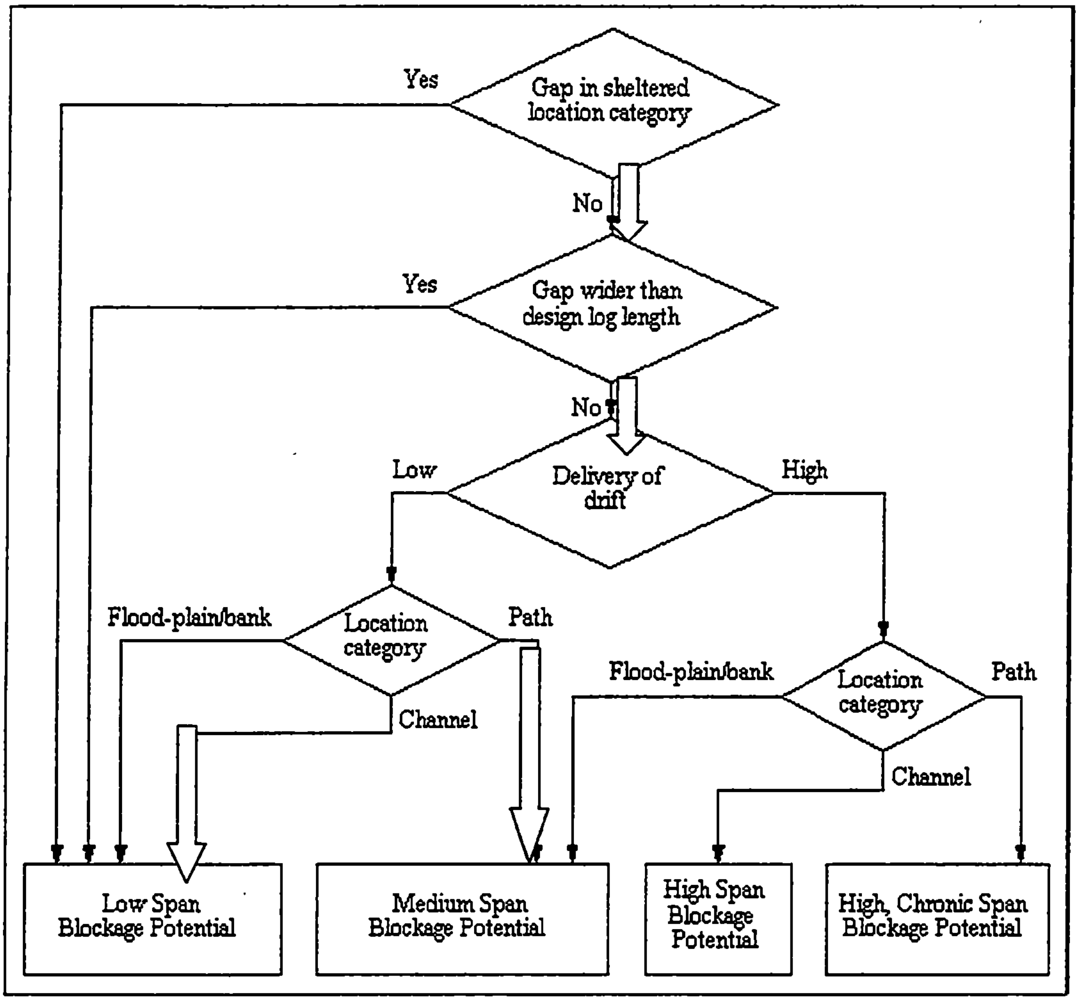


Figure C3 – Flow chart for determining potential for drift accumulation across a bridge span or vertical gap.(from Diehl, 1997)

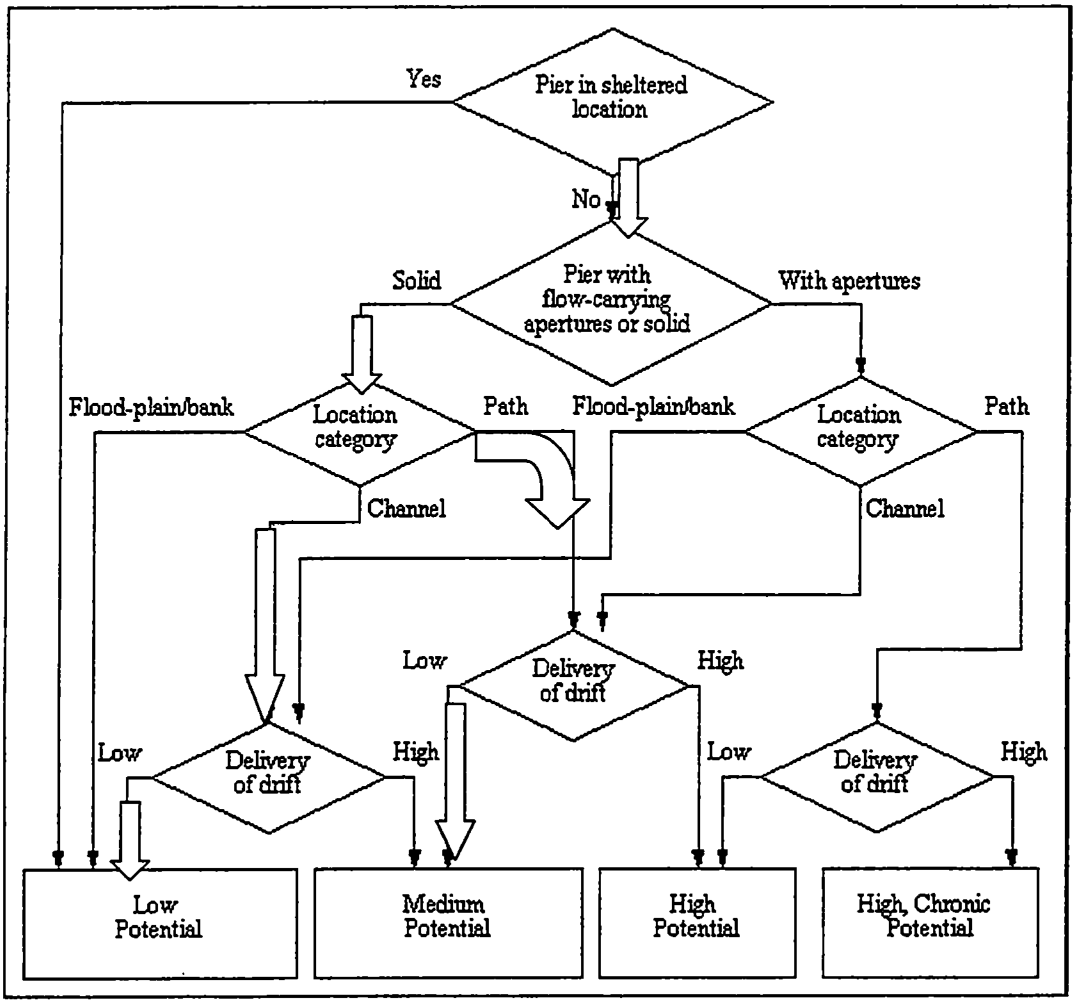


Figure C4 – Flow chart for determining potential for drift accumulation on a single pier.
(from Diehl, 1997)

```
            Program run number 1

            DEBRIS AT BRIDGE PIER CALCULATIONS

The tree trunk diameter (Dt) is 1 metres
The tree root wad/canopy diameter (Db) is 6 metres
The average tree height (Ht) is 12 metres
The observed number of trees likely to appraoch the bridge in the
upstream reach (N) is 3

The bridge pier diameter parallel with the flow (l) is 0.9 metres
The bridge pier diameter normal with the flow (D) is 0.9 metres
The span between bridge piers across the flow (Ls) is 10 metres
The flow depth (Y) is 10 metres

====================================================================
======================================================================


Bridge Pier Scour Results :
The following values have been calculated by assuming all (N) 3 trees
are caught at the bridge
The probability  of at least 1 out of 3 trees becoming trapped is 100%

Flow intensity factor (Kl) is 2.4
Sediment size factor (Kd) is 1
Flow depth factor (Ky) is 1
Pier shape factor (Ks) is 1
Pier alignment factor (Ka) is 1
```

(Estimated data for scour calculations: $D_{50} = 0.09$ mm, $\sigma = 10$, $D_{max} = 150$ mm, $V_1 = 2.4$ m/s, $K_\alpha = 0$)

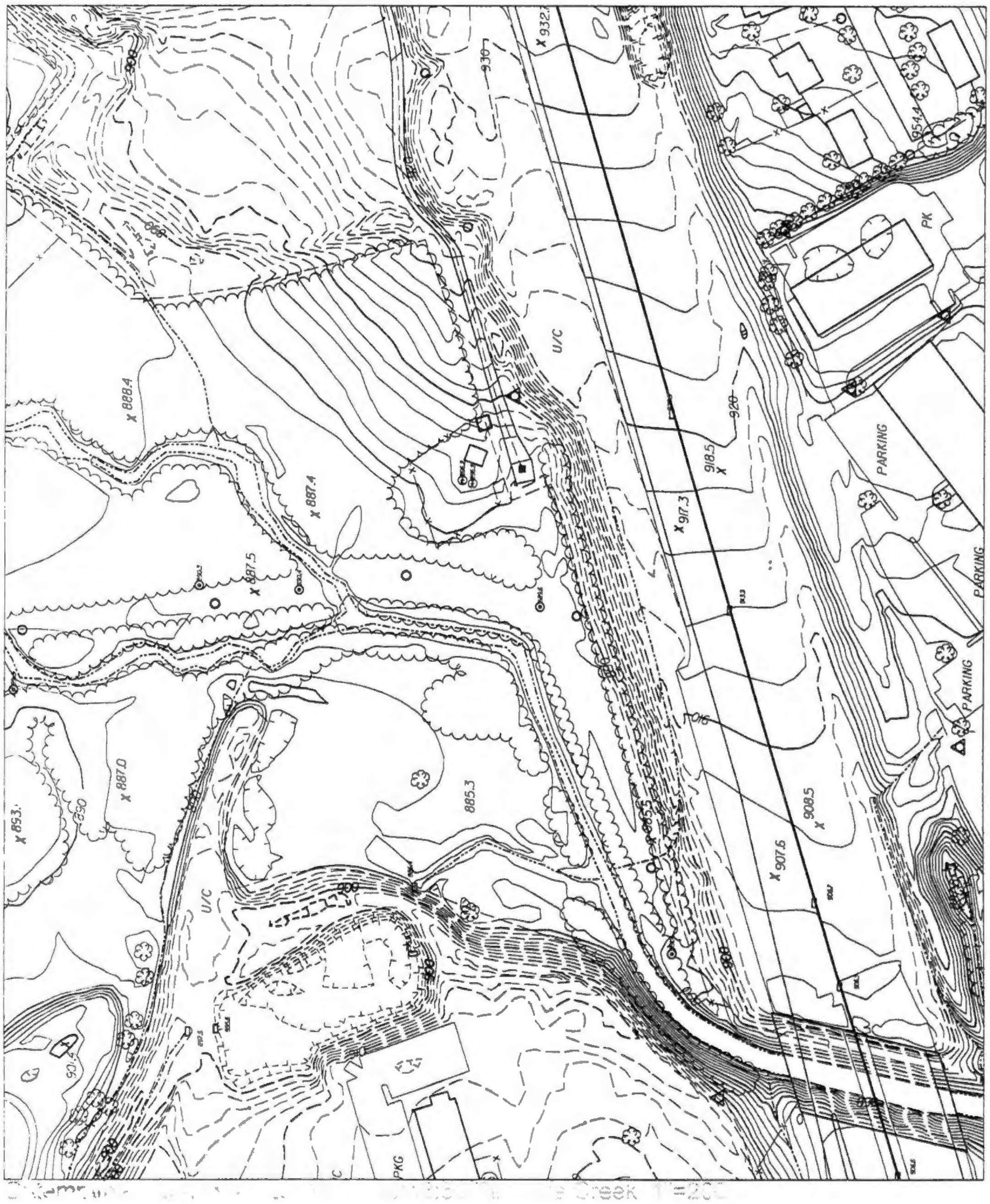


Figure C5 – Topography of the Interstate 40 / 75 Bridge Site.(1"=200')

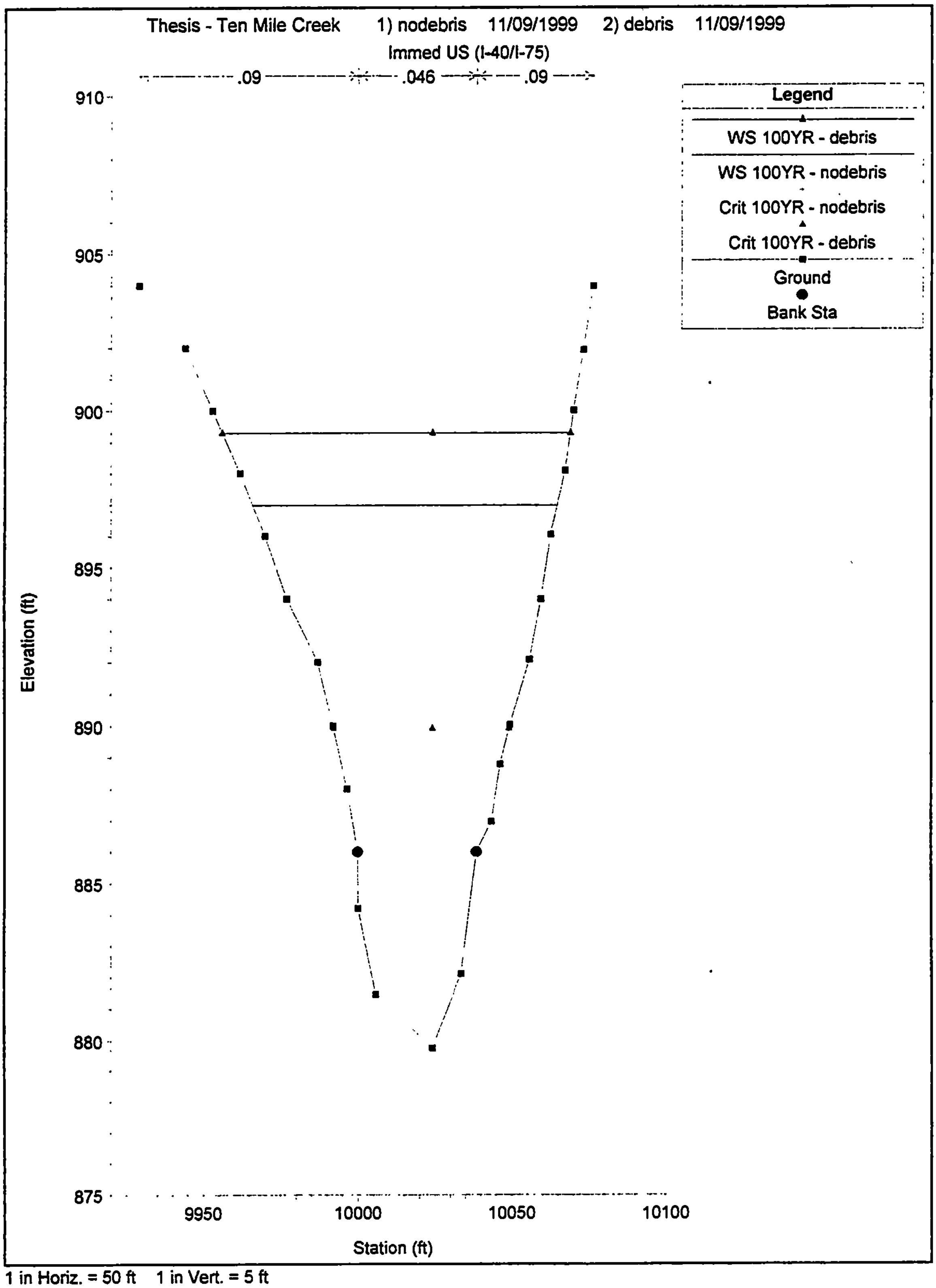


Figure C6 – Immediately Upstream Cross Section from Interstate Highway 40 / 75 Bridge.

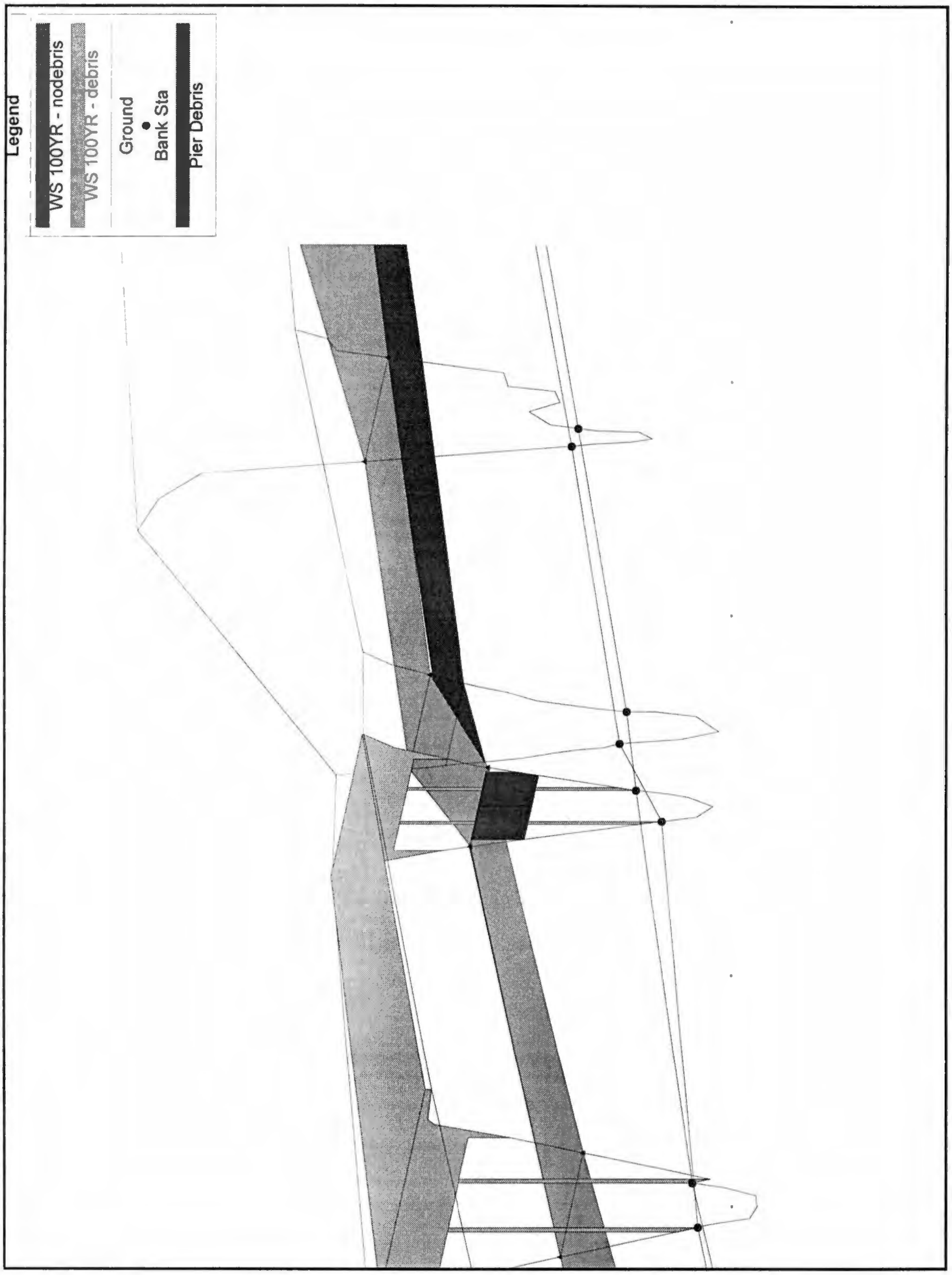
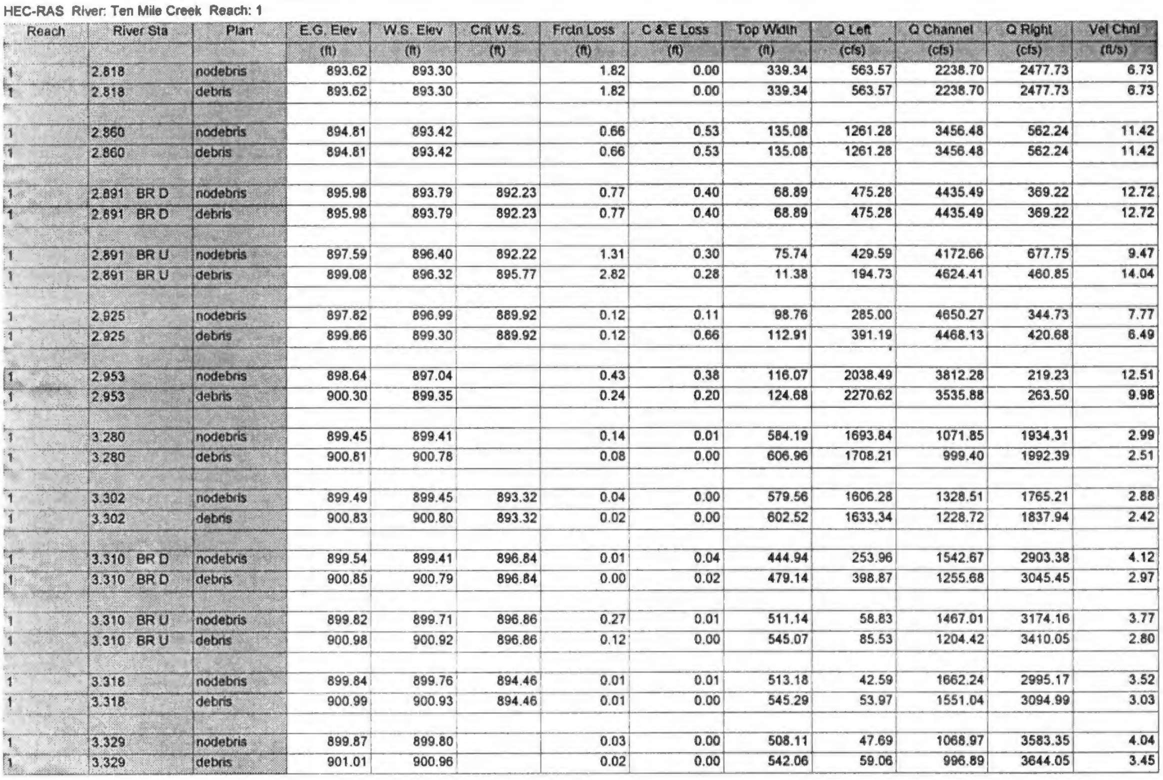


Figure C7 – XYZ Plot of Interstate 40 / 75 Bridge and Upstream Reach.

HEC-RAS River: Ten Mile Creek Reach: 1

Reach	River Sta	Plan	Q Total	Min Ch El	W.S. Elev	Crit W.S.	E.G. Elev	E.G. Slope	Vel Chnl	Flow Area	Top Width	Froude # Chl
			(cfs)	(ft)	(ft)	(ft)	(ft)	(ft/ft)	(ft/s)	(sq ft)	(ft)	
1	2.440	nodebris	5340.00	876.90	885.96	885.96	887.30	0.012132	12.59	1036.77	353.17	0.81
1	2.440	debris	5340.00	876.90	885.96	885.96	887.30	0.012132	12.59	1036.77	353.17	0.81
1	2.636	nodebris	6070.00	880.50	891.47		891.81	0.002643	7.39	1940.05	282.51	0.41
1	2.636	debris	6070.00	880.50	891.47		891.81	0.002643	7.39	1940.05	282.51	0.41
1	2.818	nodebris	5280.00	880.10	893.30		893.62	0.001791	6.73	2043.99	339.34	0.34
1	2.818	debris	5280.00	880.10	893.30		893.62	0.001791	6.73	2043.99	339.34	0.34
1	2.860	nodebris	5280.00	881.30	893.42		894.81	0.005840	11.42	817.90	135.08	0.61
1	2.860	debris	5280.00	881.30	893.42		894.81	0.005840	11.42	817.90	135.08	0.61
1	2.891		Bridge									
1	2.925	nodebris	5280.00	879.76	896.99	889.92	897.82	0.001705	7.77	915.73	98.76	0.35
1	2.925	debris	5280.00	879.76	899.30	889.92	899.86	0.000990	6.49	1160.91	112.91	0.27
1	2.953	nodebris	6070.00	881.00	897.04		898.64	0.005353	12.51	954.90	116.07	0.59
1	2.953	debris	6070.00	881.00	899.35		900.30	0.002787	9.98	1232.57	124.68	0.43
1	3.053	nodebris	6070.00	884.70	899.11		899.14	0.000240	2.79	5887.53	571.63	0.13
1	3.053	debris	6070.00	884.70	900.59		900.62	0.000160	2.44	6748.71	588.78	0.11
1	3.184	nodebris	4550.00	884.80	899.28		899.31	0.000248	2.53	5729.37	875.79	0.12
1	3.184	debris	4550.00	884.80	900.71		900.72	0.000142	2.05	6996.18	904.84	0.10
1	3.280	nodebris	4700.00	885.70	899.41		899.45	0.000337	2.99	4430.95	584.19	0.15
1	3.280	debris	4700.00	885.70	900.78		900.81	0.000207	2.51	5246.32	606.96	0.12
1	3.302	nodebris	4700.00	885.80	899.45	893.32	899.49	0.000337	2.88	4326.21	579.56	0.14
1	3.302	debris	4700.00	885.80	900.80	893.32	900.83	0.000209	2.42	5127.31	602.52	0.11
1	3.310		Bridge									
1	3.318	nodebris	4700.00	885.80	899.76	894.46	899.84	0.000450	3.52	3685.02	513.18	0.17
1	3.318	debris	4700.00	885.80	900.93	894.46	900.99	0.000298	3.03	4307.75	545.29	0.14
1	3.329	nodebris	4700.00	885.70	899.80		899.87	0.000608	4.04	3555.98	508.11	0.20
1	3.329	debris	4700.00	885.70	900.96		901.01	0.000395	3.45	4168.49	542.06	0.16
1	3.460	nodebris	6070.00	888.51	900.40		900.59	0.001867	6.29	2789.47	492.02	0.35
1	3.460	debris	6070.00	888.51	901.35		901.49	0.001234	5.43	3273.52	529.91	0.29
1	3.521	nodebris	6070.00	889.50	901.08		901.22	0.001873	5.81	2649.84	398.39	0.32
1	3.521	debris	6070.00	889.50	901.81		901.93	0.001395	5.24	2947.06	414.23	0.28
1	3.539	nodebris	6070.00	890.20	901.24		901.35	0.000988	4.37	3205.81	454.23	0.25
1	3.539	debris	6070.00	890.20	901.93		902.02	0.000749	3.98	3523.23	464.19	0.22
1	3.662	nodebris	4660.00	892.10	901.96		902.13	0.001784	5.72	1854.38	278.81	0.33
1	3.662	debris	4660.00	892.10	902.48		902.63	0.001426	5.30	2000.63	283.10	0.29
1	3.757	nodebris	6070.00	896.80	903.11	901.47	904.15	0.017332	12.54	886.90	355.84	0.94
1	3.757	debris	6070.00	896.80	903.35	901.47	904.31	0.015022	12.02	929.00	358.33	0.88

Table C1 – HEC-RAS Standard Output Table.



HEC-RAS River: Ten Mile Creek Reach: 1

Reach	River Sta	Plan	E.G. Elev	W.S. Elev	Crit W.S.	Frctn Loss	C & E Loss	Top Width	Q Left	Q Channel	Q Right	Vel Chnl
			(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(cfs)	(cfs)	(cfs)	(ft/s)
1	2.818	nodebris	893.62	893.30		1.82	0.00	339.34	563.57	2238.70	2477.73	6.73
1	2.818	debris	893.62	893.30		1.82	0.00	339.34	563.57	2238.70	2477.73	6.73
1	2.860	nodebris	894.81	893.42		0.66	0.53	135.08	1261.28	3456.48	562.24	11.42
1	2.860	debris	894.81	893.42		0.66	0.53	135.08	1261.28	3456.48	562.24	11.42
1	2.891 BR D	nodebris	895.98	893.79	892.23	0.77	0.40	68.89	475.28	4435.49	369.22	12.72
1	2.891 BR D	debris	895.98	893.79	892.23	0.77	0.40	68.89	475.28	4435.49	369.22	12.72
1	2.891 BR U	nodebris	897.59	896.40	892.22	1.31	0.30	75.74	429.59	4172.66	677.75	9.47
1	2.891 BR U	debris	899.08	896.32	895.77	2.82	0.28	11.38	194.73	4624.41	460.85	14.04
1	2.925	nodebris	897.82	896.99	889.92	0.12	0.11	98.76	285.00	4650.27	344.73	7.77
1	2.925	debris	899.86	899.30	889.92	0.12	0.66	112.91	391.19	4468.13	420.68	6.49
1	2.953	nodebris	898.64	897.04		0.43	0.38	116.07	2038.49	3812.28	219.23	12.51
1	2.953	debris	900.30	899.35		0.24	0.20	124.68	2270.62	3535.88	263.50	9.98
1	3.280	nodebris	899.45	899.41		0.14	0.01	584.19	1693.84	1071.85	1934.31	2.99
1	3.280	debris	900.81	900.78		0.08	0.00	606.96	1708.21	999.40	1992.39	2.51
1	3.302	nodebris	899.49	899.45	893.32	0.04	0.00	579.56	1606.28	1328.51	1765.21	2.88
1	3.302	debris	900.83	900.80	893.32	0.02	0.00	602.52	1633.34	1228.72	1837.94	2.42
1	3.310 BR D	nodebris	899.54	899.41	896.84	0.01	0.04	444.94	253.96	1542.67	2903.38	4.12
1	3.310 BR D	debris	900.85	900.79	896.84	0.00	0.02	479.14	398.87	1255.68	3045.45	2.97
1	3.310 BR U	nodebris	899.82	899.71	896.86	0.27	0.01	511.14	58.83	1467.01	3174.16	3.77
1	3.310 BR U	debris	900.98	900.92	896.86	0.12	0.00	545.07	85.53	1204.42	3410.05	2.80
1	3.318	nodebris	899.84	899.76	894.46	0.01	0.01	513.18	42.59	1662.24	2995.17	3.52
1	3.318	debris	900.99	900.93	894.46	0.01	0.00	545.29	53.97	1551.04	3094.99	3.03
1	3.329	nodebris	899.87	899.80		0.03	0.00	508.11	47.69	1068.97	3583.35	4.04
1	3.329	debris	901.01	900.96		0.02	0.00	542.06	59.06	996.89	3644.05	3.45

Table C2 – HEC-RAS Six XS Bridge Output Table.

Vita

Thomas Mihlbachler graduated with the Bachelor of Science degree in Civil Engineering from Rose-Hulman Institute of Technology in November 1996. Afterwards, he interned for six months at the Institute for Automation and Communication (ifak) in Magdeburg, Germany, developing sewer simulation software. Upon returning to the United States, he attended graduate school at the University of Tennessee with a Graduate Teaching Assistantship in the Civil Engineering Hydraulics Laboratory. The Master of Science degree in Environmental Engineering was awarded December 1999.

He is currently working for Ogden Environmental and Energy Services, Inc., at their East Tennessee branch office.