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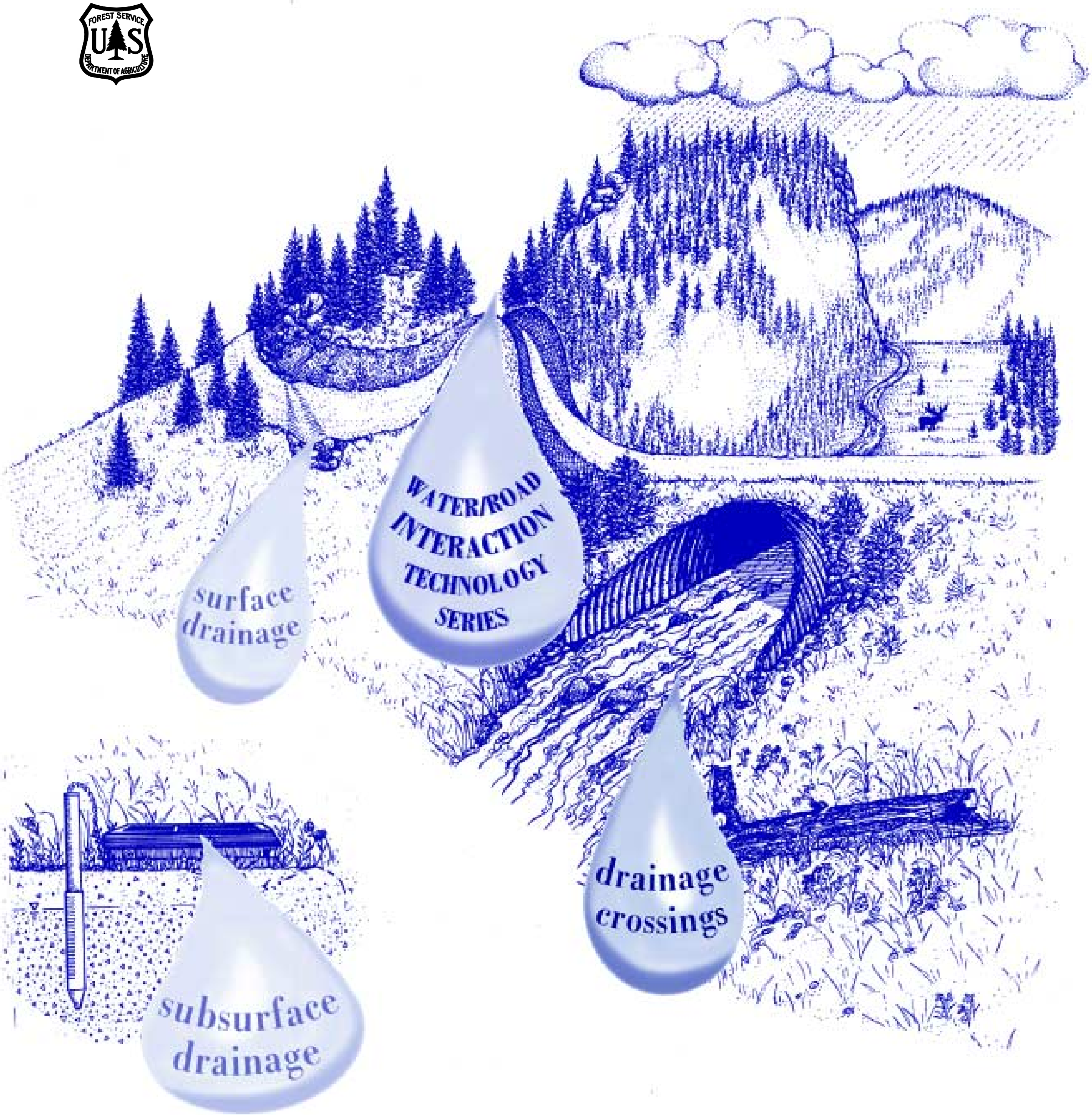
# A Guide to Computer Software Tools for Culvert Design and Analysis



# A GUIDE TO COMPUTER SOFTWARE TOOLS FOR CULVERT DESIGN AND ANALYSIS

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# Contents

## INTRODUCTION

Forest engineers and hydrologists regularly calculate design culvert dimensions for use in wildland road-stream crossings. This project investigates existing software tools to aid resource managers in culvert design and analysis requirements for low volume forest roads.

Computer models can make culvert design and analysis less cumbersome, but not all software products will meet the designer's needs.

### How to Use This Guide

This guide is a snapshot of information on software tools for culvert design and analysis gathered as of June 1998. To select a cost-effective software product that meets design needs, the reader can:

1. Look sequentially at all the tables, particularly the product review summary, which compares all the products. The tables, in order, are

   | | |
   |---|---|
   | Table 1. | Stream Crossing Culvert Design Considerations |
   | Table 2. | Factors for Inlet and Outlet Control |
   | Table 3. | Product Reviews |
   | Table 4. | Culvert Product by Focus |
   | Table 5. | Input Data |
   | Table 6. | Output Data |
   | Table 7. | Criteria Weighting Factors |
   | Table 8. | Selection Matrix Example |

2. Read the paper.

3. Follow the decision matrix methodology suggestions located in appendix A.

A glossary of terms and notations is presented in appendix B, and a decision matrix with selected criteria is presented in appendix A.

## OBJECTIVES

The objectives of this study were to provide background information on culvert design and analysis and to locate and inventory existing computer software for use in culvert design and analysis. Products were evaluated with two questions in mind: what does the product do, and how does it do it?

## SCOPE

This paper

- Compares commercial software applications used to size culverts
- Considers products for use on DOS, Windows, Macintosh, and UNIX operating systems
- Evaluates programs designed for use as stand-alone products
- Includes larger programs designed for river or watershed system analysis containing strong culvert modeling components
- Contains a glossary of culvert design and analysis terms
- Includes a system for making a software choice based on user needs

but does not

- Consider watershed modeling tools without culvert components, geographic information systems, engineering computer-aided design packages without a culvert component, storm and sanitary pipe modeling, or
- Make recommendations or ratings of products.

Because no central organized database for locating software exists, it was necessary to develop sources of software information. These sources included interviews with U.S. Department of Agriculture (USDA) Forest Service personnel; private and transportation agency hydraulic and hydrologic engineers; on-line Internet searches of World Wide Web sites; software catalogs; literature and book reviews; trade journals; professional magazines and product literature. This guide is not a comprehensive list of products, but does give a good overview of features found on current market products. The guide is not complete; new software is constantly being developed and current products are being upgraded, making a definitive comparison of culvert design software impractical.

## CULVERT DESIGN AND ANALYSIS

### Goals

The principal goal of culvert design is to determine the size, alignment, and functionality of the culvert with respect to passage requirements. In addition to the flow of water, a culvert must pass woody debris and sediment and allow passage of aquatic species. The term “size” refers to the dimensions of the barrel, including the culvert diameter and length. Alignment considers the culvert placement, usually horizontal, respective to stream flow direction and road centerline. Functionality refers to the culvert operations under given conditions and includes culvert hydraulic capacity. Additional goals of design include structural stability, durability, cost, ease of maintenance and safety (Gribben 1997).

According to Donahue and Howard (1987), the greatest source of error in culvert design is in design flow analysis. The complex array of variables that influence runoff, statistical uncertainties associated with hydrologic analysis, and a lack of comprehensive assessment methodology contribute to this error. Given this initial source of variability, a design goal is to minimize additional error wherever possible, particularly in the selection of culvert size and the determination of outlet velocity.

### Design Criteria

The selection of design criteria for a particular culvert is a function of many interacting factors including culvert hydraulics, watershed hydrology, and land management activities, according to Pyles (1989). Design criteria for a culvert installation are unique to a given installation; however, the list of items in table 1 should be considered for any culvert installation (Pyles 1989). Not all the items will pertain to every installation.

### Design Phases

Three phases are considered in culvert design. Phase one evaluates the hydrologic demands placed on the culvert. Phase two looks at culvert specifications and site considerations. And phase three evaluates culvert hydraulics. In addition to the American Iron and Steel Institute (1994 and 1995) handbooks on drainage design, Gribben (1997) and Ramsbottom et al. (1997) are comprehensive sources of complete culvert design theory with applications. The following schematic (figure 1) combined with terms in the glossary (appendix B) illustrate concepts and definitions used in culvert design and by the software products.

#### *Phase 1-Hydrology*

Design begins with the choice of a design storm, a parameter usually determined by policy or rules (for example, the 100-year design storm). After the design storm is determined, the discharge through the culvert can be computed. In some instances, this discharge may be chosen by the designer or varied to determine culvert performance. Design storm estimators include the Rational Method, regional regression equations, and the SCS (National Resource Conservation Service) curve method. American Iron and Steel Institute (1994 and 1995) summarizes the many methods. Peak volumetric flow rate, which is conveyed through the culvert, is ultimately a result of rainfall intensity and duration. This information can be in the form of actual rainfall events, representative design storms, intensity duration frequency curves, or a statistical analysis of rainfall records.

For culverts on steep forested wildlands, debris and sediment plugging cause culvert failure more frequently than peak flow capacity exceedence. (Furniss et al. 1998). Because the software reviewed in this paper incorporates flow rate as the initial design criteria, careful and judicious use of software for culverts on steep slopes is encouraged.

#### *Phase 2-Culvert Specifications and Site Considerations*

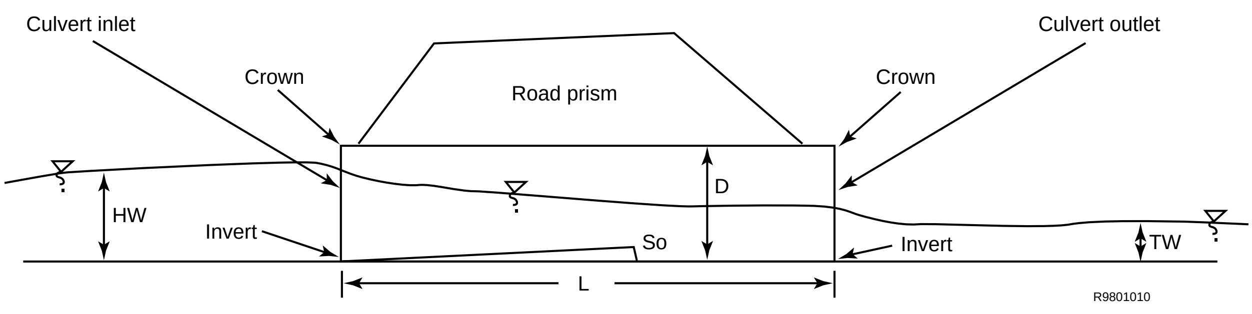
An existing drainage or the need for ditch relief on a road segment usually dictates culvert location.

The allowable headwater depth (AWD) is the maximum depth of ponded water upstream of the culvert inlet measured vertically from the invert and

Table 1—Stream crossing culvert design considerations (adapted from Pyles 1989).

| Category | Item |
|---|---|
| Peak Flow Events | Pipe size<br>Slope<br>Entrance type<br>Freeboard<br>Ponding<br>Inlet/outlet control<br>Rainfall<br>Watershed modeling |
| Fish Passage | Migration period<br>Water velocity<br>Pipe inlet/outlet geometry<br>Water depth<br>Stability of outlet pool |
| Maintenance | Woody debris<br>Bedload<br>Maintenance funding<br>Current maintenance cycle<br>Scour effects |
| Economics | Life span<br>Costs of environmental and structural damage from failure<br>Installation costs<br>Maintenance costs<br>Replacement costs |
| Legal Requirements | Forest practice regulations<br>Construction timing |

**Profile of culvert, inlet control, inlet not submerged, and projecting inlet and outlet**




**HW - Headwater elevation**
**TW - Tailwater elevation**
**L - Barrel length**
**So - Slope of culvert**
**D - Diameter of culvert barrel**

Figure 1—Schematic design of culvert in longitudinal cross section.

controls hydraulic design. AWD may be determined by the depth of fill over the culvert, which is dictated by local topography and roadway geometry and standards. Frequently, a headwater (HW) to culvert diameter (D) ratio is specified, such as HW/D = 1, which places the allowable headwater elevation at the inlet crown of the culvert.

The choice of pipe material, shape, and size may be fixed by economics, availability, site conditions (fill, bedrock, bedload), and fish passage concerns (Gribben 1997).

Site parameters important in the design of culverts include the length and slope of the culvert alignment, allowable headwater, fill depth, and effects on inlet geometry. Fill depth is determined by design loads, local topography, roadway geometry, and standards.

### *Phase 3-Culvert Hydraulics*

Culvert hydraulic modeling conventions assume that the flow through a culvert is steady and incompressible with constant density (Donahue and Howard 1987). The cross sectional area of the culvert is assumed not to change. One of the software products evaluated will allow changes in slope within a culvert, otherwise, the slope is assumed constant.

The capacity of a culvert can be affected by upstream and downstream conditions and by the hydraulic characteristics of the culvert. Combinations of these factors can be grouped into two types of flow conditions in culverts, inlet control and outlet control (table 2). These types of flow control can also be defined by the location of the control section at the culvert inlet or outlet.

Inlet control occurs when the culvert barrel is capable of conveying more flow than the culvert inlet will accept. Water can flow out of the culvert faster than it can enter the inlet. Critical depth occurs at or near the entrance to the culvert, and the flow downstream from the inlet is supercritical. Hydraulic characteristics of the downstream channel do not affect culvert capacity. Most culverts, except those in flat terrain (less than 3 percent), are designed to operate under inlet controlled conditions (Ballinger and Drake 1995). Because the capacity is controlled by entrance geometry, minor modifications to the culvert entrance can affect hydraulic capacity with both inlet or outlet control.

Outlet control is physically more complex than inlet control (table 2). Outlet control occurs when the culvert barrel is not capable of conveying as much flow as the inlet opening will accept. Water can enter the culvert faster than it can flow through the culvert. Culvert discharge, influenced by the same factors as inlet control, is also modified by tailwater elevation and barrel characteristics. Barrel characteristics include culvert roughness, cross sectional area, length, shape, and slope. When culverts are operating in outlet control, changes in barrel characteristics or tailwater elevation will affect capacity. Hence, friction must be considered in calculating discharge and velocity (American Iron and Steel Institute 1994).

Culvert design is an iterative process. Results from hydraulic analysis might indicate that pipe size, shape, number, and materials produce conditions unacceptable to the designer. If this is the case, the designer starts over basing the next design on results obtained from the previous analysis. The approach used by Normann (1985), which is incorporated into many of the software products (see table 3), is to analyze a culvert for both types of flow control. Adequate performance under the least favorable conditions is ensured by designing for the control that is least efficient at moving water as indicated by the higher of the two (inlet or outlet control) inlet headwater elevations. The higher elevation requires more energy to pass a given flow and is, therefore, the design elevation.

## ACQUIRING INFORMATION

The above criteria serve as comparisons for each software product. Information on each product was gathered from software use, interviews, product literature, and training.

Although every effort was made for product review consistency, information may differ because not all products experienced the same level of review. The potential exists for uneven analysis as not all software products were reviewed from the full

Table 2—Factors for inlet and outlet control.

| Factor | Inlet control | Outlet control |
|---|---|---|
| Headwater elevation | X | X |
| Inlet area | X | X |
| Inlet edge configuration | X | X |
| Inlet shape | X | X |
| Culvert roughness | | X |
| Culvert shape | | X |
| Culvert area | | X |
| Culvert length | | X |
| Culvert slope | * | X |
| Tailwater elevation | X | |

*Culvert slope affects inlet control performance to a small degree, but may be neglected (Normann et al. 1985).

commercial product. See Review Level in table 3, Product Reviews, for comparison of review levels. To ensure accuracy, the product developer and distributor checked all reviews.

Each software product was evaluated using a Dell 486DE with 24 MB of RAM, 1 GB hard drive, CD-ROM or Macintosh 8100 with 36 MB of RAM, 1 GB hard drive, running System 8.0.

## INFORMATION ORGANIZATION

Information on each reviewed product is coded into a two-page summary report. These reports will be available by the summer of 1999 on the USDA Forest Service Intranet at http://fsweb.sdtdc.wo.fs.fed.us/programs/eng/w-r/eccs. Detailed information on price, platforms, names, addresses (web sites, e-mail), algorithms, source code availability, modeling techniques, and remarks are noted. Input data requirements, application results, and output formats are compiled. All products reviewed are summarized below in tables 3 and 4 for a quick comparison of costs, operating systems, application focus, and solution methodology. Product sources, vendor, and developer information for each product is found in appendix A.

## FINDINGS

Thirty-three products were considered for inclusion. Thirteen of these are not currently available or appropriate. This resulted in a review of twenty products, which are summarized in table 3. Culvert hydraulic design products, complex CAD software, and watershed modeling software with a culvert design component make up the majority of products located to date.

Most culvert design and analysis software programs are based on Federal Highway Administration (FHWA) research, primarily Normann (1985) (table 3). The cost of these products ranges widely from free to $795.00.

Software products perform a variety of functions and give the culvert modeler a wide choice of features. Not every product accomplishes all goals, so it is best to determine the culvert design needs first, compare product features, and then weight costs. Most products provide a choice of units of measure and options for defining hydrology. A few software products will model roads along with culverts to provide the opportunity for determining capacity exceedance. Tables 5 and 6 summarize all input and output features for each product.

## DISCUSSION

Software is capable of returning extremely precise results that can be misleading. Culvert software for design and analysis requires informed, experienced use, incorporating awareness to assumptions and “bugs” embedded in products. For example, pipe arch definitions differ among software products. A pipe arch described by a software product may be a structural plate pipe arch, ellipse set below grade, open bottomed culvert, or a prefabricated ‘squashed pipe.’ This information may show in cross-sectional area computational differences, variations in Manning’s n through a closed or open bottom arch, visual sketches, or results. The software product’s

Table 3—Product reviews.

| Application | Review level* | Focus | Cost | Operating system | Algorithm sources |
|---|---|---|---|---|---|
| CAP-Culvert Analysis Program | 2 3 | Culvert design and analysis | Free from ftp site, $145.00 as part of HydroCD | DOS, UNIX | Bodhaine (1969) |
| CHAN v.2 | 1 2 3 | Watershed modeling with culvert component | $259.00 | Windows 9X | Normann (1985) |
| Culvert Master | 1 2 3 | Culvert design and analysis | $495.00 | WIN 3.X, Windows 9X, NT | Normann (1985) |
| Xing-Risk | 1 2 3 4 | Hazard analysis for culvert failure | Free | WINDOWS 9X, NT | Piehl et al. (1988) |
| Drainage Calculator | 1 2 3 | Culvert design (slide rule format) | $8.00 | Hand held paper slide rule | Normann (1985) |
| DrainCalc | 1 2 3 | Drainage system design and analysis with culvert component | $295.00 | DOS, DOS Emulator in Windows | California Highway or Manning's equations |
| Eagle Point Water-shed Modeling v 7.0S | 2 3 | River modeling with culvert component | $800.00 | Windows 9X | Normann (1985) |
| Eagle Point Water Surface Profiling | 2 3 | Water surface profiles with culvert component | $800.00 | Windows 9X | HEC-2 |
| FishPass | 2 3 | Fish passage design for culverts | Free | DOS, DOS Emulator in Windows | General hydraulic theory, Powers and Orsborn |
| FishXing | 1 2 3 4 | Fish passage design for culverts | Free | WINDOWS 9X, NT | Normann (1985) Behlke et al. (1991), Behlke (1993) |
| HEC-RAS v 2.2 | 1 2 3 | River modeling with culvert component | Varies, from free download, $145.00 as part of HydroCD, $150.00 from catalogs | WINDOWS 9X, NT | Normann (1985) |
| HY-8 (Culvert Analysis) | 2 3 | Culvert design and analysis | $120.00 to $145.00 from HydroCD, possible shareware | DOS, DOS Emulator in Windows 9X | Normann (1985) |
| HYDrain | 2 3 | Culvert design and analysis, shell contains HY-8 and WSPRO (water surface profile) | $145.00 as part of HydroCD, to $350.00 from catalogs | DOS, DOS Emulator in Windows 9X | Normann (1985) |
| HydroCAD | 2 3 | Stormwater modeling with culvert component | $195.00-1195.00 | Windows 9X | unknown |

Table 3—Continued.

| Cost | Review Level* | Focus | Cost | Operating sytem | Algorithm sources |
|---|---|---|---|---|---|
| HydroCalc Hydraulics, v 1.2a | 2 3 | Culvert design and analysis | $145.00 as part of HydroCD, $29.00 for separate Windows version | Windows 3.1/9X/NT | Normann (1985) |
| HydroCulv v.1.02 | 2 3 | Culvert design and analysis | Shareware, $50.00 for manual & support | Windows 9X | General hydraulic theory |
| MacCulvert | 1 2 3 | Culvert design and analysis | Shareware | Macintosh systems | Normann (1985) |
| Quick Pipe Pro | 1 2 3 | Culvert design and analysis | $375.00 | DOS, OS/2, Win 3.1/9X/NT | Normann (1985) |
| RIVERCAD | 1 2 3 4 | River modeling with culvert component | $2690.00 | Windows 9X, NT | Normann (1985), HEC-2 |
| THYSYS | 1 2 3 | Culvert design and analysis | $5.00 from Texas DOT or $795.00 from Haestad | Windows 9X, DOS for earlier Haestad version | HEC-12 and HEC-22 |



Review Level*

| Review code | Information source | Details |
|---|---|---|
| 1 | Interviews | Product developer, marketing, users, specialists |
| 2 | Literature | Publications, product literature, WWWeb pages |
| 3 | Testing | Demo copy, evaluation copy, full commercial copy |
| 4 | Training | From developer, company engineer, classroom |

Table 4—Culvert product by focus.

| Culvert design and analysis | Watershed/river modeling with culvert component | Specialty culvert design and analysis |
|---|---|---|
| CAP-Culvert Analysis | CHAN v.2* | Xing-Risk |
| CulvertMaster* | Eagle Point Watershed* | FishPass |
| DrainCalc | Eagle Point Water Surface Profiling | FishXing |
| Drainage Calculator | HEC-RAS v 2.2* | |
| HydroCalc for Windows 95 v. 1.2a* | HydroCAD | |
| HY-8, Culvert Analysis* | RiverCAD* | |
| HYDrain* | | |
| HydroCulv v.1 | | |
| MacCulvert* | | |
| Quick PipePro* | | |
| THYSYS | | |

*Incorporates Normann (1985) as algorithm source.

definition of a pipe arch must be in agreement with the culvert designer's concept of a pipe arch.

System compatibility is critical to successful use of a software product, so it is very important to match software product to available computer equipment. There is a difference between a product that runs in DOS and one that runs in the DOS emulator mode of Windows 95. True DOS software is batch input and will not run in Windows.

Cost of the software product is a factor in any acquisition decision. In addition to the initial software purchase, the culvert designer should consider any hidden costs that may be associated with the initial purchase. If new system requirements or hardware such as a CD-ROM drive is necessary, these costs should be taken into account. Additional expenses may be associated with product support, or user manuals. Finally, costs associated with learning to use the product also need to be considered.

Be careful of "feature bloat," which is defined as unnecessary and expensive additions to products. A user-friendly product running faster and requiring less disk space is more desirable than one with many unnecessary features. The additions make the product more difficult to use. Product support and a clear and concise users' manual are vital to the successful and continued usage of a software product. They are also more important than expensive features. Some of the products reviewed are complex and include several design features. If, after careful evaluation, a total river modeling system with culvert design capabilities and CAD features are needed in a software product, the cost may be justified.

## A DECISION METHODOLOGY

One approach to this guide is to combine product information with specific needs as determined by the reader. A decision matrix with suggested criteria can be found in appendix A. The following procedure guides the user through this decision process.

Software selection begins with the resource manager, who defines a list of needs and

Table 5—Input data.

| | Unit choice | Peak flow | Flow rate | Hydrograph | User defined rainfall/hydrograph | Roadway elevation | Roadway width | Pavement choice | Ponding | Bank slope | Riprap | Depth of fill | Uses weir equations | Non-overtopping choice | Maximum allowable headwater | Inlet elevation | Inlet configuation | Inlet coefficient | Outlet elevation | Outlet configuration | Outlet coefficent | Material choices | Corrugation choices | Tailwater configuration | Shape choices | Coded size | User defined size | Slope | Breaks in slope | Length of culvert | Alignment | Fall | Negative elevations | Manning's n | Natural channel user defined | Other channel shapes | Multiple barrels | Combine multiple barrel elevations | Combine multiple barrel shapes | Watershed modeling | Fish swimming ability | Values and consequences |
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Table 6—Output data.

| | Size | Slope | Inlet controlled tailwater depth | Inlet controlled headwater depth | Inlet controlled discharge | Outlet controlled tailwater depth | Outlet controlled headwater depth | Outlet controlled discharge | Slope type | Flow regime | Energy grade line | Water depth | Flow area | Wetted perimeter | Hydraulic radius | Water srface topwidth | Froude number | Velocity at inlet | Velocity at outlet | Total discharge | Discharge over road | Discharge/barrel | Normal depth | Critical depth | Critical slope | Outlet scour | Tractive force | Rating curves | Generates report | Copy/paste to other applications | Water surface profile | Print screen | Flow duration curve | Internal note pad | Fish passage capabilities | Environmental risk assessment |
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requirements. Each product is examined or evaluated in terms of the users' desired application. A list of criteria emerges from this step. A weight is assigned to each of these, with the more important criteria having a higher value. This approach requires careful evaluation of weights, but the users can tailor the selection process to their specific needs. If the product has that feature, the chosen weight is assigned. If the product does not have the desired feature, a score of zero is assigned. A suggested weighing factor (WF) for each criterion is shown in table 7:

Table 7—Criteria weighing factors.

| WF | Descriptive statement |
|---|---|
| 2 | = very desirable feature, must have |
| 1 | = necessary for operation of software |
| 0 | = not necessary or program does not contain this feature |

*Example:* A simplified selection matrix might look like table 8. In this instance, the hydrologist researching culvert software determines the following criteria are important and assigns relative weights to each criterion. If a product meets a selection criterion, the associated weighting factor

Table 8—Selection matrix example.

| Requirements based on list of criteria | Weighting factor | Product A | | Product B | | Product C | |
|---|---|---|---|---|---|---|---|
| Rainfall modeling incorporating user defined parameters | 1 | yes | 1 | no | 0 | yes | 1 |
| Inlet/ outlet control modeling | 1 | no | 0 | yes | 1 | yes | 1 |
| Model multiple culverts in parallel or in series | 0 | yes | 0 | yes | 0 | no | 0 |
| Fish swimming abilities incorporated into design capabilities | 2 | no | 0 | no | 0 | yes | 2 |
| Total points | | | 1 | | 1 | | 4 |

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# APPENDIX A

## Decision Matrix

| SUGGESTED DECISION CRITERIA | WEIGHTING FACTOR | CAP CULVERT ANALYSIS PROGRAM | CHAN v.2 | CULVERT MASTER | XING-RISK | DRAINAGE CALCULATOR |
|---|---|---|---|---|---|---|
| UNIX Compatible | | X | | | | |
| DOS Compatible | | X | | | | |
| Windows Compatible | | | X | X | X | |
| Macintosh Compatible | | | | | | |
| Product support | | X | X | X | X | |
| Unit Choice | | X | | X | X | |
| Watershed Modeling | | | X | | | |
| Rainfall Modeling | | | X | X | X | X |
| Peak Flow | | | X | X | X | |
| Flow Rate / Discharge | | X | X | X | | |
| Roadway Modeling | | | X | X | X | |
| Normann (1985) basis for Culvert Modeling | | | X | X | | |
| Maximum Allowable Headwater | | X | | X | X | |
| Inlet /Outlet Configurations | | X | X | X | | |
| Break in Slope | | | | | | |
| Alignment | | X | | X | | |
| Fall | | X | | X | | |
| Negative Elevation | | | X | X | | |
| Multiple Barrels | | X | X | X | | |
| Shape Choices | | X | X | X | | X |
| Corrugation Choices | | | X | | | |
| Channel Definition | | X | X | X | X | |
| Hydraulic Parameters | | X | | | | |
| Size Calculation | | | | X | | X |
| Slope Calculation | | | | X | | |
| Slope Type | | | | X | | |
| Inlet and Outlet Control | | X | X | X | | |
| Scour Prediction / Tractive Forces | | | | | | |
| Fish Passage | | | | | | |
| Culvert Exit Velocity | | X | X | X | | |
| Erosion Hazard / Risk Assessment | | | | | X | |
| Water Surface Profile Data/Graphics | | | X | X | | |
| Rating Curve Output | | | | X | | |
| Generates Report | | X | X | X | X | |
| Cost of Product as of June 1998 | | Free | $459.00 | $495.00 | Free | $8.00 |
| Total | | | | | | |

## APPENDIX A — Continued.

| SUGGESTED DECISION CRITERIA | WEIGHTING FACTOR | DRAINCALC | EAGLE POINT WATER SURFACE PROFILING | EAGLE POINT WATERSHED MODELING v7.0S | FISHPASS | FISHXING |
|---|---|---|---|---|---|---|
| UNIX Compatible | | | | | | |
| DOS Compatible | | X | X | X | X | |
| Windows Compatible | | X | X | X | X | X |
| Macintosh Compatible | | | | | | |
| Product support | | X | X | X | X | |
| Unit Choice | | | X | | X | X |
| Watershed Modeling | | | X | X | | |
| Rainfall Modeling | | X | | X | | |
| Peak Flow | | | X | | | |
| Flow Rate / Discharge | | X | X | | X | X |
| Roadway Modeling | | | X | | | |
| Normann (1985) basis for Culvert Modeling | | | | X | | |
| Maximum Allowable Headwater | | X | X | X | | |
| Inlet and Outlet Configurations | | | X | X | | |
| Break in Slope | | | | | | |
| Alignment | | | | | | |
| Fall | | | | | | |
| Negative Elevation | | | | | | |
| Multiple Barrels | | X | X | X | | |
| Shape Choices | | X | X | X | | X |
| Corrugation Choices | | | X | X | X | X |
| Channel Definition | | X | X | X | X | X |
| Hydraulic Parameters | | | X | | | X |
| Size Calculation | | X | | | | |
| Slope Calculation | | X | X | | | |
| Slope Type | | | X | | | X |
| Inlet and Outlet Control | | | X | X | | |
| Scour Prediction / Tractive Forces | | X | | | | |
| Fish Passage | | | | | X | X |
| Culvert Exit Velocity | | X | X | | X | X |
| Erosion Hazard / Risk Assessment | | | | | | |
| Water Surface Profile Data/Graphics | | | X | | X | X |
| Rating Curve Output | | | | X | | X |
| Generates Report | | X | X | X | X | X |
| Cost of Product as of June 1998 | | $295.00 | $800.00 | $800.00 | Free | Free |
| Total | | | | | | |

## APPENDIX A — Continued.

| SUGGESTED DECISION CRITERIA | WEIGHTING FACTOR | HEC RAS v2.2 | HY8 | HYDRAIN | HYDROCAD v5.0 | HYDROCALC v1.2a |
|---|---|---|---|---|---|---|
| UNIX Compatible | | | | | | |
| DOS Compatible | | | X | X | X | |
| Windows Compatible | | X | X | X | X | X |
| Macintosh Compatible | | | | | | |
| Product support | | X | X | X | X | X |
| Unit Choice | | X | X | X | X | X |
| Watershed Modeling | | X | | | X | |
| Rainfall Modeling | | | X | X | X | |
| Peak Flow | | X | X | X | X | |
| Flow Rate / Discharge | | X | X | X | X | X |
| Roadway Modeling | | X | X | X | | |
| Normann (1985) basis for Culvert Modeling | | X | X | X | | X |
| Maximum Allowable Headwater | | X | X | X | | |
| Inlet and Outlet Configurations | | X | X | X | X | |
| Break in Slope | | | | | | |
| Alignment | | | | | | |
| Fall | | X | X | X | | |
| Negative Elevation | | X | | | | X |
| Multiple Barrels | | X | X | X | X | |
| Shape Choices | | X | X | X | X | X |
| Corrugation Choices | | X | | | | X |
| Channel Definition | | X | X | X | X | X |
| Size Calculation | | | X | X | | |
| Slope Calculation | | X | X | X | | X |
| Slope Type | | X | | | | |
| Hydraulic Parameters | | X | X | X | X | X |
| Inlet and Outlet Control | | X | X | X | | X |
| Scour Prediction / Tractive Forces | | X | X | X | | |
| Fish Passage | | | | | | |
| Culvert Exit Velocity | | X | X | X | X | X |
| Erosion Hazard / Risk Assessment | | | | | | |
| Water Surface Profile Data/Graphics | | X | X | X | | X |
| Rating Curve Output | | X | X | X | X | X |
| Generates Report | | X | X | X | X | X |
| Cost of Product as of June 1998 | | Free to $150.OO | $120 to $145 | $145.00 to $350.00 | $195.00 to $1595.00 | $29.00 |
| Total | | | | | | |

## APPENDIX A — Continued.

| SUGGESTED DECISION CRITERIA | WEIGHTING FACTOR | HYDROCULV v1.02 | MacCULVERT | QUICK PIPE PRO | RIVERCAD | THYSYS CULVERT v1.1 |
|---|---|---|---|---|---|---|
| UNIX Compatible | | | | | | |
| DOS Compatible | | | | X | | |
| Windows Compatible | | X | | X | X | X |
| Macintosh Compatible | | | X | | | |
| Product support | | | X | X | X | X |
| Unit Choice | | | X | X | X | X |
| Watershed Modeling | | | | | X | |
| Rainfall Modeling | | | | | X | |
| Peak Flow | | | | | X | |
| Flow Rate / Discharge | | X | X | X | X | X |
| Roadway Modeling | | | | X | X | X |
| Normann (1985) basis for Culvert Modeling | | | X | X | X | |
| Maximum Allowable Headwater | | X | X | X | X | X |
| Inlet and Outlet Configurations | | X | | | X | |
| Break in Slope | | | | | | X |
| Alignment | | | | | | |
| Fall | | | | | | |
| Negative Elevation | | | | | | |
| Multiple Barrels | | | | X | X | X |
| Shape Choices | | X | X | X | X | X |
| Corrugation Choices | | | | X | X | |
| Channel Definition | | X | X | | X | X |
| Size Calculation | | | | | | X |
| Slope Calculation | | X | X | X | | X |
| Slope Type | | X | | X | | |
| Hydraulic Parameters | | X | | X | X | X |
| Inlet and Outlet Control | | X | X | X | X | X |
| Scour Prediction / Tractive Forces | | | | X | X | |
| Fish Passage | | | | | | |
| Culvert Exit Velocity | | X | X | X | X | X |
| Erosion Hazard / Risk Assessment | | | | | | |
| Water Surface Profile Data/Graphics | | X | | | X | |
| Rating Curve Output | | X | | X | X | X |
| Generates Report | | X | X | X | X | X |
| Cost of Product as of June 1998 | | Free | Free to $100.00 | $375.00 | $2690.00 | $5.00 |
| Total | | | | | | |

## APPENDIX B

GLOSSARY OF TERMS AND NOTATIONS

Note: These definitions are specific to the subject of this report.

| | |
|---|---|
| alignment | Placement of the culvert with respect to the streamflow and road crossing. |
| allowable headwater depth (AHD) | Allowable depth of water immediately upstream of a culvert, measured from the invert at the first full cross section of the culvert. A design criteria. |
| allowable headwater elevation (AHE) | The maximum permissible depth of water surface immediately upstream of culvert at the design discharge, measured from a datum. Note: datum may differ between software applications; measured from culvert invert, or another datum. |
| arch | Structural plate corrugated steel pipe formed to an arch shape. The invert may be the natural stream bed or any other suitable material, but is not integral with the steel arch. See pipe arch for comparison. |
| backwater | The rise of water level upstream due to a downstream obstruction or channel confluence or constriction. |
| backwater curve | Water surface elevation for gradually varied flow, where changes in velocity occur very slowly, with negligible acceleration. Units are in length. |
| backwater effect | The effect that changes in flow rate or water depth have on upstream hydraulic conditions. Backwater effects can only occur in subcritical flow. |
| baffle | Obstruction, usually wood, concrete, or metal, placed inside a culvert to deflect and check the flow of water for fish passage. |
| bedload | Sediments, rocks, and boulders not in suspension, but rolled or drawn along a stream bottom by force of water movement. |
| beveled inlet | A flare on the inlet edge of a culvert to improve efficiency or capacity of inlet controlled culverts, reduces the inlet coefficient $K_e$. |
| box culvert | Short segment of closed conduit, rectangular in cross-section. |
| capacity (hydraulic) | The effective carrying ability of a drainage structure. Measured in volume per time. |
| coefficient of runoff | Percentage of gross rainfall that appears as runoff. Also ratio of runoff to depth of rainfall. Used in the Rational method for computing design discharge. |

| | |
|---|---|
| competent velocity | The velocity of water that can just move a specified type or size of streambed material. |
| corrugated metal pipe (CMP) | Galvanized steel or aluminum sheet metal formed to finished shape by the fabricator. |
| cost effective | Providing the optimum effect at the most reasonable cost. |
| critical depth | Depth of flow at which specific energy is minimum for a given flow. Not affected by downstream phenomenon. |
| critical flow | Flow at critical depth, where the sum of the velocity head and the static head is at a minimum. Flow with Froude number of 1. |
| critical slope | Slope of channel or culvert when normal depth equals critical depth. The slope at which a maximum flow will occur at minimum energy. |
| critical velocity | Mean water velocity at critical depth. |
| culvert | A hydraulically short conduit that conveys stream flow, sediment, debris, and aquatic species through a roadway embankment or past some other type of flow obstruction. |
| debris | Floating, suspended, or waterlogged woody materials moved by a stream flow. |
| design discharge | The discharge that a structure is designed to accommodate without exceeding the chosen design constraints. A quantity of flow that is expected at a certain point as a result of a design storm or flood frequency. |
| design flood | The peak discharge (when appropriate, the volume, stage, or wave crest elevation) of the flood associated with the probability of exceedence selected for the design of a highway encroachment. |
| design frequency | The recurrence interval for hydrologic events used for design purposes. As an example, a design frequency of 50 years means a storm of a given magnitude has a 2 percent (1/50) chance of being equaled or exceeded in one year. |
| design life | The length of time a structure is designed to function without major repairs or replacement. |
| design storm | A precipitation event, with a specified probability of occurring in any given year expressed in years or percentage, used as a design parameter. May also be a particular storm that contributes a design runoff, depth, duration, or frequency. |

| | |
|---|---|
| diameter (D) | Inside diameter, measured between inside crests of corrugations. |
| discharge | The volumetric rate of movement or flux of a quantity of water flowing from a drainage structure or past a given point per unit of time. Also, flow rate. |
| endpoints | Resources or facilities of value or importance that could be potentially affected by crossing failure. |
| energy grade line (EGL) | The line that represents the total amount of energy available at any point along a culvert. Where water is motionless, the water surface would correspond to the energy grade line. It is established by adding together the potential energy expressed as the water surface elevation referenced to a datum and the kinetic energy, usually expressed as velocity head, at points along the stream bed or culvert profile. |
| energy head | The sum of the hydraulic grade line at any section plus the velocity head of the mean velocity of the water in that section. |
| entrance loss | The head lost in eddies and friction at the inlet to a culvert. Also, contraction loss. |
| environmental risk assessment | Methodology for determining the likelihood of modification by to one or more values. |
| fall | A steeply inclined channel length in or immediately upstream from a culvert inlet; designed to improve culvert capacity. |
| fish passage | Movement of fish through a fishway or culvert. |
| flood frequency | Exceedence interval, recurrence interval or return period. The average time interval between occurrences of a hydrological event of a given or greater magnitude. The percent chance of occurrence is the reciprocal of flood frequency, e.g., a 2 percent chance of occurrence is the reciprocal statement of a 50-year flood event. |
| flow rate | The volume of water flowing from a drainage structure per unit of time. |
| flow area | Cross-sectional area of flow calculated on the basis of inside culvert diameter. |
| flow duration curve | Graph showing the percentage of time mean daily discharges have been equaled or exceeded. |
| flow line elevation | Elevation at the lowest point in a channel or culvert cross section. |
| flow regime | Flow classification based on Froude number, i.e., supercritical or subcritical. |

he

| | |
|---|---|
| freeboard | The height from a design water level to the top of a roadway or embankment. |
| Froude number | For a rectangular or very wide channels, $F = V/(gy_h)^{0.5}$ where F is the Froude number; a dimensions number used to determine flow regime. V is the average velocity of flow, g is gravitational acceleration, and $y_h$ is the hydraulic depth. If $F > 1.0$, the flow is supercritical and is characterized as swift, if $F < 1.0$, the flow is subcritical and is characterized as smooth and tranquil, and if $F = 1.0$, the flow is said to be critical. |
| gradient | The rate of rise or fall of a length of a line or culvert as determined by the ratio of the change in elevation to the length. Expressed as a percentage or a decimal |
| gradually varied flow | Nonuniform flow where the depth of flow changes slowly with distance. Resistance to flow dominates and acceleration forces are negligible. |
| head (static) | The height of water above any datum. |
| headwall | The retaining wall at an inlet or outlet (usually aligned at right angles to the culvert but can be skewed). |
| headwater | The height of water at the inlet of a culvert. Usually expressed as the water height relative to the diameter of the culvert, HW/D. For example, if water at the inlet is twice the height of the culvert diameter, the headwater to culvert diameter ratio is 2. |
| headwater elevation | The water surface elevation upstream from a culvert entrance invert, measured from a datum. Note: datum may differ between software applications; measured from culvert invert or another datum. |
| height of cover | Distance from crown of culvert to road surface. |
| helical CMP | Corrugated metal pipe with a continuous helical seam, either lock or welded. Has decreased roughness within the barrel compared to annular rib corrugations (lower Manning's *n* value). |
| hydraulic capacity | The maximum flow of water that a culvert can continuously pass. |
| hydraulic depth | The ratio of the flow area to the top width. |
| hydraulic design | The hydraulic capacity that a culvert is designed to accomodate. |
| hydraulic grade line (HGL) | A line representing the total potential energy; a combination of energy from the height of the water and internal pressure. In an open channel, this corresponds to the water surface. |
| hydraulic jump | A sudden transition from supercritical flow to subcritical flow, which is caused by a higher downstream depth, producing a rise in water surface elevation. |

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|---|---|
| hydraulic radius | The ratio of flow area to wetted perimeter. |
| hydrograph | A graph of stage, discharge, velocity, runoff, or inflow over time. |
| inlet | The upstream entrance of a culvert. |
| inlet control | Culvert flow capacity determined by inlet shape characteristics and headwater depth. |
| inlet/outlet crown | The uppermost outside point on a cross section of a culvert. |
| invert | The flowline at the inside lowest point of a culvert cross section. |
| long span culverts | Culverts that are designed on structural aspects rather than hydraulic considerations. Usually constructed of structural plate. |
| maintenance cycle | Frequency of inspection, routine cleaning, and repair. |
| Manning equation | An empirical equation used to estimate friction loss and discharge in culvert design. Incorporates channel roughness, hydraulic radius, and cross-sectional area of flow. Assumes uniform flow or gradually varied flow. |
| Manning's n | An empirical coefficient relating the effect of channel boundary or culvert roughness to energy losses in flowing water. |
| normal depth | Depth of water at normal flow, where discharge, velocity, and depth do not change with length. |
| outlet | The downstream end of a culvert; the outfall. |
| outlet control | Culvert flow capacity determined by the barrel roughness, length, slope, and tailwater elevation. |
| performance curve | A plot of culvert discharge versus inlet headwater elevation or depth. |
| pipe arch | A corrugated metal pipe shaped to a span (width) greater than rise (height), structurally continuous, usually prefabricated. |
| projecting end | A culvert inlet or outlet that projects from the face of the fill or embankment. Also called a perched or shotgun culvert. |
| rapidly varied flow | Nonuniform flow where depth of flow changes rapidly over a relatively short distance, such as a hydraulic jump. |
| rating curve | A curve that correlates flow rates to flow depths in a channel or culvert. |
| rational method | An approach to estimate the rate of storm runoff based on an intensity-runoff relationship; Q=CIA. C is the coefficient describing runoff potential of an area, I is the rainfall intensity during the core time of concentration, and A is the drainage or watershed area. |

| | |
|---|---|
| return period ($T_r$) | The average period of time expected to elapse between successive storm event occurrences of a given size or larger. It is not a statistical guarantee that a damaging storm will appear on schedule, rather, it is the reciprocal statement of probability (p): $T_r = 1/p$. |
| rise | The maximum vertical height inside a culvert, usually measured at the center line. |
| risk analysis | Assessing the probability of failure and values at stake for alternate culvert designs. |
| runoff | The part of precipitation and snowmelt that reaches streams and eventually the sea by overland and subsurface flow. This is the stream flow before it is affected by artificial diversion, impoundments, or other manmade changes in or on stream channels. |
| scour | Degradation of the channel at the culvert outlet as a result of erosive velocities. |
| skew | The acute angle formed by the intersection of the line normal to the centerline of the road with the centerline of a culvert. Also, the angle formed between the centerline of the culvert and the channel thalweg. |
| slope | (1) The gradient of a stream; (2) Inclination of the face of an embankment, expressed as the ratio of the horizontal to vertical projection; (3) the face of an inclined embankment or cut slope. Expressed as a percent or decimal. |
| slope type | Water surface profiles classified according to channel slope type (mild, steep, critical, horizontal, or adverse). |
| steady flow | Discharge, velocity and depth of flow constant through time. |
| subcritical flow | Flow at velocities less than critical, with a Froude number less than 1. Gravity forces are more pronounced than inertial forces. Flow has a lower velocity and is often described as steady, tranquil, or streaming. |
| supercritical flow | Flow at velocities greater than critical, with a Froude number greater than 1. Inertial forces are dominant, so the flow has a higher velocity and is usually described as rapid or shooting. |

| | |
|---|---|
| surface profile type | First letter of the type of slope (M, S, C, H, or A) combined with the actual depth of flow in relation to the critical and normal depths (Zone 1: actual flow depth is greater than both normal and critical depths; Zone 2: flow depth is between the normal and critical depths; or, Zone 3: flow depth is less than both normal and critical depths). An example is S2. |
| tailwater depth | Depth of water immediately downstream from a culvert, measured from the culvert outlet invert. |
| tailwater elevation | Depth of water immediately downstream from a culvert, measured from a datum. |
| time of concentration | The time required for storm runoff to flow from the most remote point of a drainage area to the point of consideration. It is usually associated with a design storm. |
| topwidth | Chord describing free surface extent of water in a culvert. |
| tractive force | Drag or shear that is developed on the wetted area of a channel by erode material. Acts in the direction of flow, related to scour. |
| uniform flow | Depth of flow not varying with distance, implied that flow is also steady. |
| unsteady flow | Discharge, velocity and depth of flow changing with time. |
| water depth | Measurement from culvert invert, pool or channel bottom to water surface. |
| water surface profile | A profile plot of water surface elevation through a culvert or open channel. |
| wetted perimeter | The cross-sectional length of wetted contact between the water prism and the culvert, measured at right angles to the culvert. |
| wingwalls | The retaining walls that provide a transition from the culvert headwall to the channel. |