STREAM SYSTEMS TECHNOLOGY CENTER

STREAM NOTES

To Aid In Securing Favorable Conditions of Water Flows

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Providing for Stream Function and Aquatic Organism Passage: An Interdisciplinary Design

by Traci L. Sylte

Culverts are commonly used to permit water to flow beneath roads where they cross streams, thereby preventing road erosion and allowing water to follow its natural course. From mountain regions, to lowland cities and counties, there is abundant evidence of culverts inadequately providing for aquatic organism passage and stream structure (Figure 1).

Historically, water has been viewed as a liability in road design that needs to be managed to avoid destroying an investment such as the road (Copstead, 1997). Despite many standards and guidelines that address the importance of fish movement, the number of culverts either partially or fully impeding passage is high (GAO, 2001). Although the impact of any one culvert in most cases is not substantial, cumulatively, impacts can be significant. The United States has hundreds of thousands of roads, resulting in millions of culverts – many on important water quality and fish streams.

Fish passage through culverts and highway structures is an old topic, but as the number and range of many aquatic species have declined, the importance of protecting the remaining populations has multiplied (Votapka, 1991). Research has also increased awareness and knowledge of the extent of this problem. The term "fish passage" inadequately characterizes the need. Rather "aquatic organism passage" appropriately describes the issue as it includes other species such as amphibians, reptiles, and, even mollusks (Warren et al., 2000; Williams et al, 1992).

Historical Perspective

Four primary issues explain the large number of existing inadequate culverts:

- Former design approaches,
- Lack of cross-disciplinary communication and understanding,
- Salmo- and adult-centric knowledge and application, and
- New knowledge and awareness.

In the past, engineers focused on hydraulic efficiency as the dominating criteria in culvert design. In most instances, little regard was given to other passage considerations such as bedload, debris, and fish. Culvert size primarily resulted from calculating how much discharge the culvert could accommodate evaluated with the risk of experiencing a discharge that would exceed hydraulic capacity and the consequential replacement or repair costs.

Engineers often were unaware of passage issues, or they lacked the information needed

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CONTRIBUTIONS *are voluntary and will be accepted at any time. They should be typewritten, single-spaced, and limited to two pages. Graphics and tables are encouraged. E-Mail: jpotyondy@ fs.fed.us*

CORRESPONDENCE:
E-Mail: rmrs_stream@ fs.fed.us
Phone: (970) 295-5983
FAX: (970) 295-5988
Web Site:
http://www.stream.fs.fed.us

Figure 1. Bank undercutting at culvert outlet effectively preventing the passage of fish and other aquatic organisms.

to design a structure that would allow fish passage. Typically, fish biologists lacked the culvert hydraulics information needed to make an informed recommendation, or they were untrained in hydraulics and were unaware of the magnitude and/or duration of undesirable hydraulic conditions within the culvert. In other words, the paths of fish biologists and engineers simply failed to cross frequently enough and other priorities and emphasis areas impeded active communication.

When fish passage was a focal issue, engineers and fish biologists tended to focus on salmon and trout species. In addition, passage of adult life-stages was given primary importance because it was thought that if the adult species could reach spawning areas, juvenile species did not need consideration.

Research in the past ten years has provided much insight into the timing of fish movement, swimming capabilities, and metapopulation dynamics. This knowledge has increased our awareness of the problem extent and how cumulative impacts are fragmenting populations. Passage considerations of species such as amphibians, mollusks and even reptiles have largely gone unrecognized. Combined with other mechanisms of resources impacts (primarily movement impediment, habitat alteration and fragmentation), culverts are now considered an issue for these species as well.

Fundamental Interactions

Understanding the fundamentals of both fish-stream interaction and culvert-stream interaction is necessary to understand why culvert-passage problems exist, and to develop successful solutions. The stream is the important process link.

Generally speaking, the highest stream velocities occur in the middle of flow volume with much lower velocities occurring along channel margins. In many streams, the boundary is highly irregular – dominated with different substrate sizes, bedform irregularities, large wood, root matter, and bank irregularities. Consequently, velocities near the channel bed and bank are commonly 0-3 ft/sec under normal runoff conditions.

Fish and other aquatic organisms live and travel primarily along these channel margins. This is the environment under which they evolved and developed their swimming capabilities, although some species such as salmon have evolved into stronger fish because of the long distances and obstacles encountered along long migration routes.

Understanding that average stream velocities are 3-6 ft/sec for bankfull flow conditions, helps to understand how velocities inside the culvert can easily exceed average stream velocities when culverts constrict the active channel width. If roughness differences between the stream and culvert bottoms are considered, velocities during runoff conditions may exceed 4-5 ft/sec even for culvert gradients as low as 1-2 percent, even if the active channel width is not constricted. One does not need sophisticated knowledge of culvert hydraulics or models to look at a culvert and assess the likelihood of organism passage difficulties.

Stream and Culvert Interaction

Culverts commonly constrict the active (e.g., bankfull) stream channel width. The stream has developed this width in response to the sediment, debris, and water produced in the watershed. When culverts constrict this width, a series of stream adjustments frequently occurs and culvert failure risk increases.

Culverts more commonly fail due to capacity reductions associated with debris or bedload blockage upstream of the inlet (Flanagan and Furniss, 1997). Having the culvert span the active channel width can prevent the majority of these failures. If the culvert is wider than the channel width, most debris will pass through the culvert.

Spanning the active channel width can also minimize aggradation due to bedload deposition upstream of the inlet. As flow begins to pond, above the culvert inlet, velocity decreases and bedload is deposited. Stream flow correspondingly erodes the stream banks causing stream widening upstream of the inlet.

These backwater conditions increase inlet headwater depths and velocities within the culvert, eroding the culvert outlet. This scour can lower local stream base levels and result in undercutting of adjacent slopes. Backwater conditions can also saturate the road fill, which can cause culvert piping and/or road overtopping conditions (Figure 2). Debris torrents from one failed crossing can cause failure of the next lower crossing, setting in motion a series of domino-effect failures.

Fish Needs and Capabilities

Culverts commonly impede fish movement by one of the following mechanisms:

- Excessive velocities,
- Excessive outlet perch heights,
- Inadequate depths for fish migrating during lower flow conditions, or
- Debris blockage at the inlet.

Fish move for a variety of reasons, including feeding, avoidance of unfavorable conditions, optimization of reproductive success, and optimization of colonization. Due to differences in evolution, fish commonly move to access desirable spawning areas at different times of the year. Considering multiple species and spawning times with the need for fish to avoid undesirable conditions leads to the conclusion that fish need to migrate during all times of the year. Consequently, culverts should provide passage whenever fish are present.

Figure 2. Culvert failure resulting from water piping.

The swimming capabilities of fish differ greatly by species and between life-stages. Generally, weaker swimming fish are the limiting factor in passage considerations. Common terminology for the various speeds involves darting, sustained, and cruising speeds. These speeds are analogous to a dash, a short sprint, or a marathon. Depending on the site conditions, fish commonly must use a combination of darting and/or sustained swimming speeds to negotiate through a culvert. Both consume a large quantity of energy and can only be maintained for short distances.

Conclusions

Properly designed culverts do not produce water velocities that exceed fish swimming abilities (Behlke, C. et al., 1991). Properly designed culverts also accommodate stream structure and function, which in most cases means at least spanning the active channel width. Installing adequately-sized structures such as bottomless box culverts or arches, countersunk culverts (Figure 3), bridges, or fords accomplishes these tasks.

Due to the integration of multiple physical and biological elements, an interdisciplinary approach is essential. New, user-friendly tools for assessing and modeling culvert hydraulics are available. Software packages, such as FishXing (USDA Forest Service, 2000) for example, allow for the modeling

Figure 3. Counter-sunk pipe arch culvert. The stream channel is simulated through the crossing.

of culvert hydraulics concurrently with fish swimming capabilities. Additional information, field inventory forms, and an annotated bibliography for designing fish crossings are available at the Web site http://www.stream.fs.fed.us/fishxing.

A holistic, interdisciplinary approach to culvert design creates a win-win scenario for all interested parties. Engineers, hydrologists, and fish biologists can often agree on a mutually beneficial stream crossing designs. Culverts that constrict streams produce velocities that often exceed organism capabilities. If the culvert avoids constricting the active channel width, bedload and debris passage will be provided for under most circumstances. Spanning the active channel and simulating a channel bottom through the culvert will satisfy most biological and hydrologic concerns.

For the engineer, planner, and manager, the initial costs of designing for aquatic passage will likely increase because the culvert will be larger and thus more expensive. However, failure risks will be reduced and structure life will be optimized. Maintenance levels and replacement frequency will decrease creating more economic opportunities with limited budgetary resources.

Finally, it is time to consider an economic reality check. Having the least expensive crossing alternatives and still maintaining aquatic organism passage, stream function, maximized structure life, and minimized maintenance costs are unrealistic.

Integrating culverts, streams, and aquatic organism passage is a win-win scenario that ultimately will lead to more viable aquatic populations, healthier streams, and engineering maintenance budgets that can focus resources elsewhere.

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Traci L. Sylte, Hydrologist and Professional Engineer, U.S. Forest Service, Lolo National Forest, Missoula, MT. (970) 295-5987, tsylte@fs.fed.us. Traci is presently on temporary assignment with the Stream Systems Technology Center in Fort Collins.

A Sampling Frame for Improving Pebble Count Accuracy in Coarse Gravel-Bed Streams

Improved sampling techniques are needed to increase the accuracy of pebble count particle-size distribution measurements in gravel-bed streams. Researchers Kristin Bunte and Steven Abt of the Engineering Research Center at Colorado State University have developed a 60 by 60 cm sampling frame (Figure 1) to standardize the sampling process of selecting particles from sand to cobbles in gravel-bed rivers.

Pebble counts are prone to operator errors introduced through subjective particle selection, serial correlation, and inaccurate particle-size measurement. Errors in particle-size measurement can be minimized by using a gravel template. Operator influence on particle selection can be minimized by using a sampling frame in which sampling points are identified by the cross points of thin elastic bands. Serial correlation can be minimized by adjusting the spacing between the cross points and setting them equal to the dominant large particle size (approximately D_{95}).

The traditional way of particle selection in a pebble count by a blind touch at the tip of the boot allows an operator to have a large influence, voluntarily or involuntarily, on particle selection. Selecting a particle where the operator places his/her feet is not an objective means of particle selection, because when wading in coarse gravel and cobble-bed streams, an operator may be reluctant to step on top of a slippery cobble or boulder for risk of insecure footing. Thus, cobbles and boulders are less likely to be selected.

Whereas foot placement tends to bias against cobbles, the blind touch aspect using the tip of the finger tends to bias against small particles surrounded by large particles. This happens because as the finger reaches down, the sides of large neighboring particles are more likely to be touched before the finger touches smaller particles. Using the grid, fine particles can be precisely identified visually and the operator can then concentrate on retrieving just that particle.

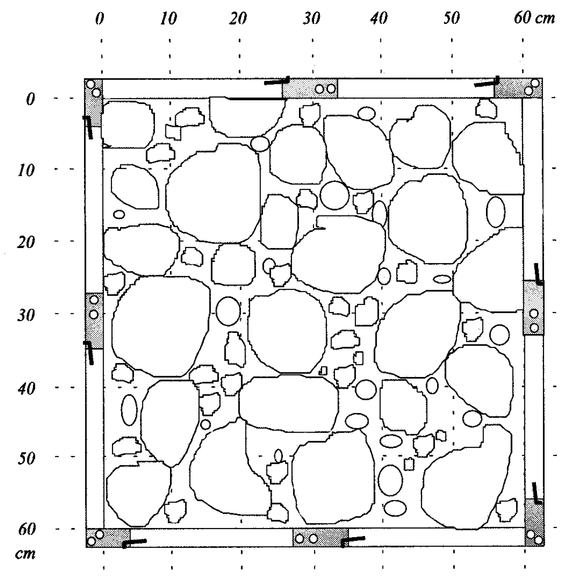


Figure 1. Eight-piece 60 by 60 cm collapsible sampling frame constructed from aluminum bars. An adjustable grid of thin white elastic bands are stretched horizontally and vertically across the frame to define the exact particles to sample. When the frame is placed onto the stream bed, the elastic bands stretch across the cobbles that protrude above the bed.

Reducing operator bias leads to reduced variability between operators. Samples from two operators that varied substantially in heel-to-toe walks were nearly identical when using the sampling frame.

Complete details can be found in: Bunte, K., and S.R. Abt, 2001. Sampling frame for improving pebble count accuracy in coarse gravel-bed streams. Journal of the American Water Resources Association, 37(4): 1001-1013.

Kristin Bunte, Fluvial Geomorphologist, Colorado State University, Fort Collins, CO; (970) 491-3980; kbunte@engr.colostate.edu.

Steven R. Abt, Professor, Civil Engineering, Colorado State University, Fort Collins, CO; (970) 491-8203; abt@lance.colostate.edu.

Excel Spreadsheets for Statistically Analyzing Pebble Count Data

Two separate Excel 2000 spreadsheet-workbooks have been developed to assist with the statistical analysis of pebble count data. One is designed to assist with the proper implementation of the zig-zag pebble count procedure, while the other can be used to perform similar analyses on pebble count data tallied by size class. The thrust of each analysis is to identify shifts in the fine gravel and smaller portions of the distribution, rather than the median.

Zig-Zag Pebble Count Analyzer

The Zig-Zag Pebble Count Analyzer was developed by Greg Bevenger, Forest Hydrologist, Shoshone National Forest, and Rudy King, Station Statistician, Rocky Mountain Research Station, to help users properly implement the zig-zag pebble count procedure (Bevenger and King, 1995. A pebble count procedure for assessing cumulative watershed effects. Rocky Mountain Forest and Range Experiment Station Research Paper RM-RP-319, 17 pages). The zig-zag method is a pebble count procedure using a zig-zag sampling pattern along a longitudinal stream reach such that a stream is sampled along a continuum instead of an individual site, reach, or cross-section. By doing this, numerous meander bends and all associated habitat features are sampled as an integrated unit rather than as individual cross-sections.

Macro enabled worksheets are provided to help users: (1) estimate sample size, (2) enter field data, (3) produce tables and graphs, (4) perform statistical analysis using contingency tables and the Pearson chi-squared statistic, and (5) make notes. The spreadsheet-workbooks also contain case studies to illustrate typical application of the procedure and provides examples of typical analysis scenarios. The intent is to assist users with the development of study plans and to help them interpret results.

Figure 1 illustrates typical contingency table output. Additional information about the statistical analysis is included in the spreadsheet to help users properly interpret the results. Complete description of the statistics is included in RM-RP-319 and users are cautioned to become thoroughly familiar with the paper before proceeding. Figure 2 shows example tabular and graphic output from one of the case studies. The graphs show the departure of the study pebble count from the reference pebble count, particularly for the smaller size classes.

Size-Class Pebble Count Analyzer

The Size-Class Pebble Count Analyzer was developed to allow analysis of pebble count data tallied by size class. This spreadsheet was developed by John Potyondy, Hydrologist, Stream Systems

Contingency Tables

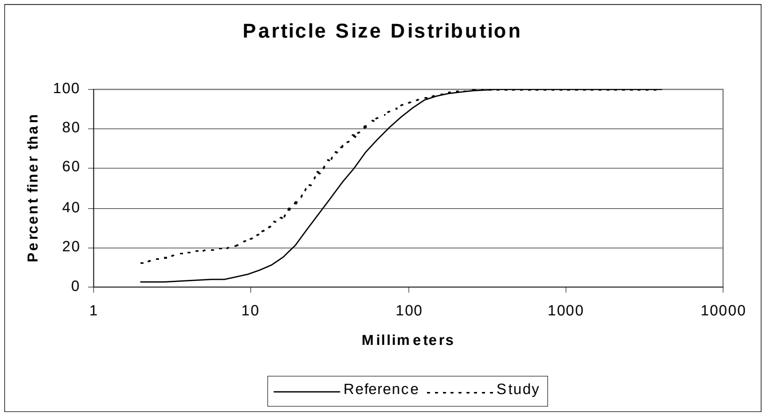
4 mm			
	<	> or =	Total
Reference	32	968	1000
Study	27	123	150
Total	59	1091	1150
Reference <	Study <	Average <	Average >=
3.2%	18.0%	5.1%	94.9%
		p-value	<.0001

6 mm			
	<	> or =	Total
Reference	42	958	1000
Study	32	118	150
Total	74	1076	1150
Reference <	Study <	Average <	Average >=
4.2%	21.3%	6.4%	93.6%
		p-value	<.0001

8 mm			
	<	> or =	Total
Reference	56	944	1000
Study	32	118	150
Total	88	1062	1150
Reference <	Study <	Average <	Average >=
5.6%	21.3%	7.7%	92.3%
		p-value	<.0001

Figure 1. Example contingency tables produced by the analyses spreadsheet. Summary data are presented as (1) total number of pebbles counted that are less than and greater than the designated particle size criterion and (2) percentage of pebbles counted that are less than the designated particle size criterion. Also presented is a p-value for each particle size criterion. A small p-value (for instance, less than 0.05) indicates that the proportion of particles less than the criterion is probably different between your reference and study reaches.

Cumulative Distribution		
Class	Reference	Study
2	3	13
4	3	18
8	6	21
16	15	36
32	45	65
64	75	85
128	95	96
256	100	100
512	100	100
1024	100	100
2048	100	100
4096	100	100



Histogram		
Class	Reference	Study
2	3	13
4	1	5
8	2	3
16	10	15
32	30	29
64	30	21
128	20	11
256	5	4
512	0	0
1024	0	0
2048	0	0
4096	0	0

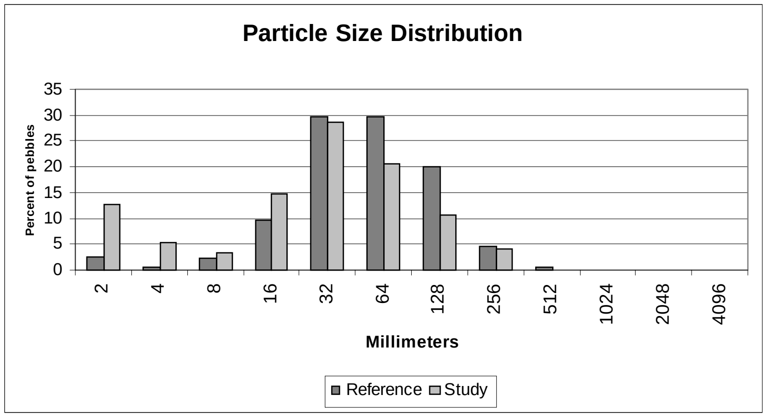


Figure 2. An example of particle size tabulations and particle size distribution and histogram plots automatically generated by the analysis spreadsheets.

Technology Center, and Kristin Bunte, Fluvial Geomorphologist, Colorado State University to be similar to that developed by Bevenger and King. The size-class pebble count analyzer assumes that sampling is geomorphically stratified based on the natural sorting of grain sizes into distinct channel features to sample homogeneous populations. Depending on study objectives, this may involve sampling in riffles, pools, or combinations of riffles and pools. The intermediate axis is measured with a ruler or a gravel template (gravel-o-meter) and tallied into standard Wentworth size classes. Potyondy and Bunte strongly recommend the use of templates because they avoid incorrectly identifying the intermediate axis and have been shown to reduce error among observers.

Additional information about pebble counts is available in Bunte, K. and S.R. Abt, 2001, Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring, Rocky Mountain Research Station RMRS-GTR-74, 428 pages.

How to Obtain Spreadsheets

Copies of the Excel 2000 spreadsheet-workbooks Zig-Zag Pebble Count Analyzer (v1) and Size-Class Pebble Count Analyzer (v1) are available for downloading from the STREAM Web page (http://www.stream.fs.fed.us) by going to the “downloads” area and double clicking on one of the above file names to initiate the download.

If you have questions about or need assistance using the size-class spreadsheets, contact John Potyondy, (970) 295-5986, jpotyondy@fs.fed.us. If you have questions about the zig-zag spreadsheets, contact Greg Bevenger, (307)-527-6241, gbevenger@fs.fed.us.

Rocky Mountain Research Station publications RM-RP-319 and RMRS-GTR-74 are available from RMRS Publications Distribution: (970) 498-1392, or e-mail rschneider@fs.fed.us.

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STREAM SYSTEMS TECHNOLOGY CENTER
USDA Forest Service
Rocky Mountain Research Station
2150 Centre Ave., Bldg A, Suite 368
Fort Collins, CO 80526-1891

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The Federal Interagency Sedimentation Project (FISP) Sediment Measuring Equipment

Research conducted by FISP originally focused on hydraulic and mechanical aspects of sediment sampling, but has expanded to include development of sample-analysis methods, development of automatic in-situ analyzers, and sampling techniques and equipment for sampling water quality in streams and rivers. The equipment and techniques of FISP are the standards used by most Federal, State, and local governments, and private organizations collecting sediment samples in the United States.

FISP is only authorized to sell directly to Federal agencies of the United States. However, official FISP equipment is now available to everyone through private distributors. Check out the FISP Web site at http://fisp.wes.army.mil/ or call (601) 634-2721 for information.