

FINAL REPORT

# NONANADROMOUS FISH PASSAGE IN HIGHWAY CULVERTS



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Supplementary Notes				
<p><b>Abstract</b></p> <p>Highway culverts may hinder the normal migrations of various trout species in wild trout streams, due to increased flow velocity, shallow water depths, increased turbulence, and perching. This can impede migrational movements, affecting the genetic diversity and long-term survival of some species. Often, the proper installation of culverts can reduce the adverse effects on fish while maintaining hydraulic efficiency. This study characterized the problems with existing culverts to develop guidelines for the future use of culverts in high-gradient streams. Installation criteria will ideally limit the use of bridges where culverts are appropriate, and eliminate the use of culverts where they would cause fish passage problems. This will reduce installation, maintenance, and retrofitting costs. Culverts can be the primary option for crossing trout streams where the following criteria are met:</p> <ol style="list-style-type: none"> <li>1. The culvert can be placed on the same slope as that of the streambed.</li> <li>2. The slope of the stream is less than three percent.</li> <li>3. The flow velocity does not exceed 1.2 meters/second under normal flow conditions.</li> <li>4. The barrel of the culvert can be properly countersunk at the outlet to prevent perching.</li> </ol> <p>Where the criteria cannot be met, bridges should be used. Also, baffles should not be used to control streamflow velocities in new culverts, and concrete aprons should not be used at culvert outlets. If culvert bottoms could be cast to have a roughness coefficient equal to that of the streambed, this would allow greater use of culverts at stream crossings without impeding the passage of trout.</p>				

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**(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)**

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## ABSTRACT

Highway culverts may hinder the normal migrations of various trout species in wild trout streams, due to increased flow velocity, shallow water depths, increased turbulence, and perching. This can impede migrational movements, affecting the genetic diversity and long-term survival of some species. Often, the proper installation of culverts can reduce the adverse effects on fish while maintaining hydraulic efficiency. This study characterized the problems with existing culverts to develop guidelines for the future use of culverts in areas with high gradient streams. Installation criteria will ideally limit the use of bridges where culverts are appropriate, and eliminate the use of culverts where they would create fish passage problems. This will reduce installation, maintenance, and retrofitting costs. The study concluded that culverts can be considered the primary option for crossing trout streams if the following criteria are met:

- the culvert can be placed on the same slope as that of the streambed
- the slope of the stream is less than three percent
- the flow velocity does not exceed 1.2 meters/second under normal flow conditions
- the barrel of the culvert can be properly countersunk at the outlet to prevent perching.

Bridges should be used at these crossings if any of the above criteria cannot be met. Also, baffles should not be used to control streamflow velocities in new culverts, and concrete aprons should not be used at culvert outlets. If culvert bottoms could be cast to have a roughness coefficient equal to that of the streambed, this would allow greater use of culverts at stream crossings without impeding the passage of trout.

## **Final Report**

### **Nonanadromous Fish Passage in Highway Culverts**

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#### **BACKGROUND**

There are approximately 2,200 miles of wild trout streams in Virginia (Mohn, 1994; Sloane, 1992). Highway culverts in these streams may hinder the normal migrations of various trout species. Increased flow velocity, shallow water depths, increased turbulence, and perching of streams can impede migrational movements, affecting the genetic diversity and long-term survival of some species. Often, the proper installation of culverts can reduce the adverse effects on fish while maintaining hydraulic efficiency (Baker & Votapka, 1990; McClellan, 1970; Votapka, 1991).

When hydraulically feasible, it is generally more cost-efficient to construct culverts than comparably sized bridges. Bridges can cost up to three times as much to install (\$60-\$70/ft<sup>2</sup> of bridge deck) and up to ten times as much to maintain. However, as problems associated with fish passage become more evident, the Virginia Department of Transportation is coming under increasing pressure from various state agencies to install bridges rather than culverts where streams known to provide habitat for trout are crossed. Bridges often do not hinder the migrational movements of fish since stream flow characteristics are not altered once construction is complete.

Fish passage through highway culverts has been studied extensively along much of the east coast and in the eastern part of Virginia. Most of this research has been on anadromous fish (saltwater fish that migrate to fresh water to spawn). In Virginia alone, there have been several studies (Mudre, Ney, & Neves, 1985; Odum, Neves, Ney, & Mudre, 1986; Odum, Neves, & Ney, 1988a; Odum, Neves, & Ney, 1988b) of the impact of highway culverts on anadromous fish passage. However, resident (nonanadromous) species located in areas with high gradient streams have been studied much less. While resident species do not migrate to the extent that anadromous fish do, during their normal lifecycle it is not uncommon for them to migrate several kilometers upstream or downstream (Helfrich & Kendall, 1982). Meyers, Thuemler, and Kornely (1992) studied the movements of brown trout over a two year period. Results of their research indicated that brown trout move much greater distances than previously thought in the spring and fall. Typical migrational distances were greater than 15 kilometers. The movement of resident trout is related to the search for feeding and spawning locations (Helfrich & Kendall, 1982; Meyers et al., 1992). Trout are also known to move upstream to escape

rising water temperatures, as they cannot survive temperatures much above 70° F. Impasses, therefore, contribute to an increase in genetic segregation and a decline in species diversity (McCormick, Naiman, & Montgomery, 1985; Sloane, 1992; Votapka, 1991). The few studies of nonanadromous species have taken place primarily in the western United States, in Alaska, Washington, Utah, and Montana. Many of the same species are found in Virginia. To what extent the findings from these studies apply to fish and culverts in Virginia is not known.

## **PROBLEM STATEMENT**

VDOT does not have guidelines specifying when to use culverts rather than bridges when crossing high gradient streams that are known to provide habitat for nonanadromous fish species. This can result in culverts being improperly installed with respect to fish passage in these areas. Most environmental regulatory agencies would prefer that VDOT install bridges at all stream crossings serving as habitat for trout, which can result in the use of bridges where culverts would be acceptable.

## **PURPOSE AND SCOPE**

The purpose of this study is to characterize the problems with existing culverts in order to develop guidelines for the future use of culverts in areas with high gradient streams. The characterization of the existing fish passage problems and the development of installation criteria will ideally limit the use of bridges where culverts can be installed without causing passage problems for resident fish species. Additionally, the criteria will eliminate the use of culverts where such structures would create fish passage problems regardless of installation methods. This will result in cost savings in two ways: (1) by installing culverts rather than bridges, installation and maintenance costs will be reduced dramatically; (2) by installing bridges where culverts are not sufficient for fish passage, corrective action and retrofitting costs will be reduced.

## **METHODS**

The research project had two main tasks: a literature review and a field survey. The literature review was conducted to determine the maximum swimming speeds subject species could maintain for given distances, the minimum water depth in the culvert barrel required for passage, and the maximum outfall height that could be maneuvered. The literature search also revealed what other states have done to prevent the impedance of nonanadromous fish species, and determined culvert parameters that allow or prevent the passage of nonanadromous species.

The field survey portion of the study was designed to validate the findings of the literature review and determine the culvert attributes that allow or impede the passage of fish in Virginia streams. The survey took place in the Salem and Staunton Districts due to the number and density of trout streams in those areas. Streams, and specifically culvert locations, were selected based on species location information from the Virginia Department of Game and Inland Fisheries. Streams known to serve as habitat for wild trout (as opposed to hatchery reared trout) were selected. Fish species sampled included brook trout (*Salvelinus fontinalis*), rainbow trout (*Onchorynchus mykiss*), and brown trout (*Salmo trutta*), the three common trout species found in high gradient streams in Virginia.

An initial survey was conducted on approximately 25 culvert locations in southwest Virginia (Figure 1). These sites were examined with respect to the parameters outlined in the literature review, and six of the sites were chosen for additional measurements and sampling for the presence of trout.

Culvert-specific information collected in the field included depth of flow and stream flow velocity, which was measured at 0.6 of the flow depth using a Teledyne Gurley Model 622 flow meter. Measurements were taken at the inflow, middle, and outflow sections of the culvert. Culvert length and slope and streambed slope both up and downstream of each of the culverts were measured. Each outlet pool was examined for characteristics affecting flow, such as width, depth, and presence of debris. The outfall height (distance from bottom of culvert at outlet to the top of the outlet pool) was measured and recorded, as was the presence of hydraulic jumps (abrupt, turbulent rise in the water surface depth) near the inlet or outlet.

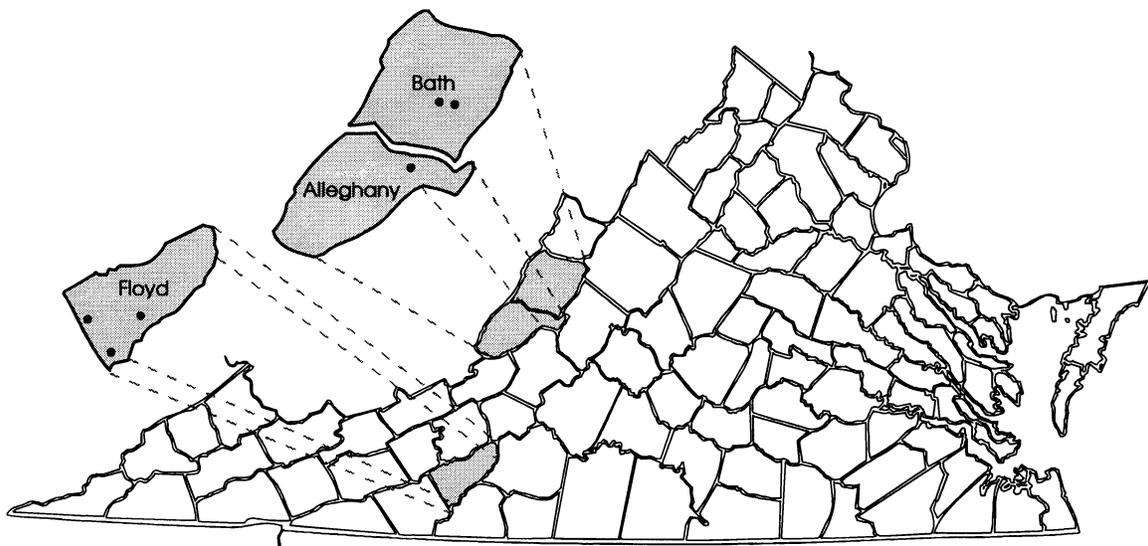


Figure 1. Culvert locations in southwest Virginia.

The presence of trout was determined by electrofishing, using a Smith & Root model 11-A fish shocker. Areas immediately downstream and upstream as well as the culvert barrels were sampled. Fish species were collected, identified, clipped according to procedures outlined in Everhart, Eipper, and Youngs (1953), and logged. All fish were then released downstream of the culvert. Streams were resampled approximately four weeks later to determine if any of the trout had moved upstream through the culverts. Culvert barrels were observed during each of the site visits to determine if the trout could move through the structures.

## RESULTS

### Literature Review

A significant amount of research has attempted to characterize the problems associated with fish passage at culvert structures. Much of this work was done for various midwestern species. The results summarized here are primarily for the three species of trout found in Virginia streams. Appropriate general information is also included. Parameters for the impedance or passage of fish defined in the literature mostly involved flow velocity or water depth. Other parameters included the maximum outfall height that can be maneuvered, the use of concrete aprons at the entrance or exit of the culvert, and the maximum slope of the culvert barrel.

*Maximum Swimming Speed.* Values for the maximum speed of trout species varied significantly from source to source. Much of the research done on maximum velocity was conducted many years ago, but should still be accurate. Typical values ranged from 1.7 (Evans & Johnston, 1972) to 3.9 meters per second (Watts, 1974). These are “burst speeds” that can only be maintained for several seconds.

*Maximum Flow Velocities.* The recommended maximum flow velocities for nonanadromous trout species are listed in Table 1. In addition to these specific values, Baker and Votapka (1990) suggested that the maximum flow velocity of a culvert not exceed the natural stream velocity of a 10-year flood. No explanation at how to arrive at this stream velocity was provided. The use of baffles to control flow velocities was not recommended under normal circumstances (Baker & Votapka, 1990; Votapka, 1991; Lauman, 1976).

**Table 1. Maximum Flow Velocities Maneuvered  
by Nonanadromous Fish Species**

Source	Maximum Flow Velocities (meters/second)
Belford & Gould (1989)	<b>1.32</b>
Bell (1973)	<b>1.46</b>
Lauman (1976)	<b>1.22</b>
Saltzman & Koski (1971)	<b>1.22</b>
Travis & Tilsworth (1986)	<b>1.38</b>

All values are for velocity of water at 0.6 total water depth.  
Values are for culverts approximately 10 meters in length.

*Minimum Water Depth.* Minimum water depth values allowing passage through a culvert for most trout species ranged in the literature from a low of 8 cm (Saltzman & Koski, 1971) to a high of 30 cm (Bell, 1973). Lauman (1976) and Baker & Votapka (1990) concluded that minimum depths of 12 and 15 cm respectively were required. However, this minimum primarily depended on the size of the fish, with larger fish requiring a greater depth of flow.

*Outfall Height.* Baker and Votapka (1990) recommend that all culverts be countersunk at least 15 cm to prevent perching at the outlet. The state of Maryland, as a part of their overall fish passage program, requires that all newly installed culverts be countersunk a minimum of 30 cm (Leasner, 1995). Lauman (1976) indicated that adult trout could maneuver an outfall height of approximately 15 cm. Nearly all references indicated that the bottom of the culvert at the outfall should be below the outlet pool, preventing any type of barrier as a result of perching.

*Concrete Aprons.* Concrete aprons at the ends of culverts have been used to prevent scour resulting from high flow velocities. They are normally used in conjunction with corrugated metal pipe arch culverts. Because of their decreased roughness coefficients, flow across them actually accelerates and thins, often resulting in passage impedance. It is therefore recommended that aprons not be used (Lauman, 1976; Votapka, 1991).

*Maximum Slope.* The slope at which culverts should be placed is undoubtedly the most highly debated issue concerning fish passage through culverts. There are many different theories in the literature regarding the maximum gradient at which culverts should be placed to prevent fish passage impedance. Several sources indicated that the slope of the culvert should always be 0 percent (Bell, 1973; Dryden, 1979; Evans, 1972). Other sources indicated that slopes of 0.5 percent were acceptable (Baker & Votapka, 1990).

Several sources indicated that slopes of up to 5 percent could be made acceptable, but only with some type of baffling system (Dryden, 1979; Votapka, 1991).

## Field Survey

### *Culvert Parameters*

Of the 25 culverts that were examined in the original field survey, 15 were excluded from further investigation for one of several reasons: they were obviously not a barrier to fish movement, the stream that passed through them was extremely small (in two cases completely dry), they were bottomless, or there was some other type of barrier immediately downstream. The flow velocities and water depths for the six culverts that were chosen for sampling are shown in Table 2. The approximate slope and the resultant stream velocities and water depths are shown in Figure 2.

**Table 2. Culvert Parameters  
for Sites Sampled for Trout**

#	Location	Outlet Velocity (m/s)	Center Velocity (m/s)	Inlet Velocity (m/s)	Outlet Depth (cm)	Center Depth (cm)	Inlet Depth (cm)
1	Bath County Rt. 39 over Jordan Run	0.35	1.70	1.02	27	6	6
2	Bath County Rt. 39 over Jordan Run	1.18	0.85	1.49	11	12	21
3	Alleghany Co. Rt. 606 over Piney Branch	0.34	0.10	0.10	15	9	9
4	Floyd County Rt. 758 over Laurel Creek	0.51	0.18	0.18	9	18	17
5	Floyd County Rt. 807 over Howel Creek	0.84	0.35	0.51	16	18	21
6	Floyd County Rt. 624 over Mira Fork	0.35	0.35	0.51	15	15	15

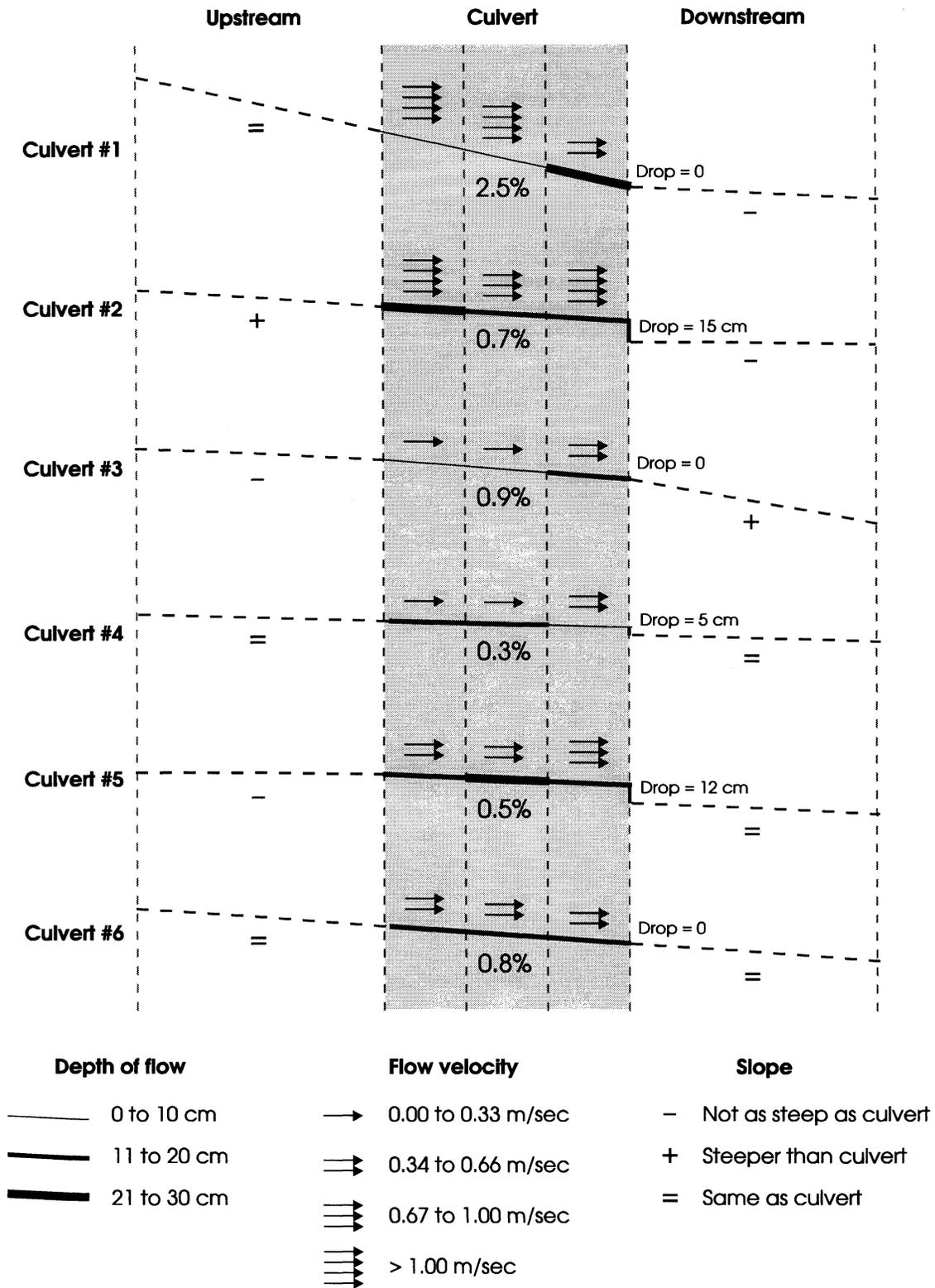


Figure 2. Culvert slopes and resultant velocities and depths.

*Fish Sampling*

During the first sampling (1) of the six culvert sites, a total of 20 brook trout were caught. Eleven were clipped, as the remainder were determined to be too small for the clipping procedure used. The number of subject species caught and their respective locations for each stream are shown in Table 3 below. The number of samples recaptured during the second sampling (2) phase, and the number of trout observed passing through the barrel of the culverts, are also shown in Table 3.

**Table 3**  
**Nonanadromous Trout Species Caught**

#	Location	Down-stream (1)	In Culvert (1)	Up-stream (1)	Clipped & Released Down-stream (1)	Down-stream (2)	Up-stream (2)	Clipped Up-stream (2)	Number Observed Passing (1 & 2)
1	Bath County Rt. 39 over Jordan Run	0	0	3	1	1	4	0	0
2	Bath County Rt. 39 over Jordan Run	4	1	2	3	1	6	0	1
3	Alleghany Co. Rt. 606 over Piney Branch	1	1	2	2	2	0	0	2
4	Floyd County Rt. 758 over Laurel Creek	1	0	1	2	0	0	0	0
5	Floyd County Rt. 807 over Howel Creek	2	0	0	2	3	0	0	0
6	Floyd County Rt. 624 over Mira Fork	1	1	0	1	0	0	0	1
	<b>TOTALS</b>	9	3	8	11	7	10	0	4

## **DISCUSSION**

### **Literature Values vs. Field Results**

Previous research on nonanadromous species indicated some reasonably specific maximums for flow velocity and outfall height that allow fish passage. The differences between values can be attributed in part to the different habitats of each experiment pool. However, in all cases the published maximum values for nonanadromous species are significantly less than those published for most anadromous species. The values obtained by the field study are similar to those found in the literature, reflecting the significantly lower values for nonanadromous fish. Any structures built meeting the more commonly published anadromous maximums/minimums would probably impede the passage of trout found in Virginia streams.

Based on the passage parameters in the literature, culvert #1 should not allow passage due to excessive flow velocities and shallow water in the culvert barrel, probably resulting from the relatively steep slope of the culvert barrel (approximately 2.5 percent). Results from the field survey matched the results of the literature, with the exception of trout moving through culverts #4 and #5. No trout were observed passing, nor were either of the two tagged trout at these sites recaptured upstream. Based on the culvert parameters (as compared to both literature and the other field values), however, it could be assumed that resident trout could pass through these structures.

The culvert parameter values obtained in the field survey portion of the study are limited by the low numbers of trout that were collected during the sampling process. Collecting tagged specimens above a culvert structure would have indicated that passage was possible for that structure under those particular flow conditions. However, no tagged specimens were later collected upstream. This does not indicate that passage was necessarily unsuccessful, because no tagged species were collected downstream either. This is due, at least in part, to the low numbers of fish that were initially tagged and the fact that most of the areas sampled are heavily fished. Fish passage was observed through three of the structures during the sampling periods. This indicates that the flow velocities, water depths, and outfall heights were maneuverable. While obviously not ideal from a statistical perspective, these low sampling and observation numbers were common to much of the published research cited here. Anadromous species, by comparison, are more likely to move in large migration runs, when larger numbers can be tagged and sampled.

### **Most Significant Hindrances**

The two most significant problems contributing to fish passage impedance in the culverts in this study were shallow depths of flow and large outfall heights. Of the six culverts studied (and the other 19 initially surveyed), only one had a flow velocity above the lowest maximum value recommended in the literature (Lauman, 1976; Saltzman &

Koski, 1971). However, it should not be assumed that the flow velocities at these sites never exceed those maneuverable by trout. During periods of high flow, the flow velocities probably increase dramatically, causing temporary conditions where passage is not possible. Field measurements were taken at a period of average spring flow under normal precipitation conditions. Delays in passage caused by temporary high flow are not as significant a problem with resident species as they are with anadromous species because migrational distances are not as great and therefore passage timing is not as critical.

### *Depth of Flow*

The depth of flow was the limiting factor for at least one of the culverts measured. The culvert in Bath County (Rt. 39 over Jordan Run) had minimal inlet and center depths, due to the culvert being placed at a higher gradient than the streambed. As the water entered the culvert, the flow accelerated, becoming supercritical (shooting or torrential flow) and thinning to a depth of approximately 6 cm (Figure 3). All six culverts had depths of approximately 15 cm in at least part of the barrel. These values are above the minimums suggested from previous research. However, as the summer progresses and stream flow volumes decrease, the depth of flow will decrease as well, impeding passage.



**Figure 3. Supercritical flow near culvert inlet.**

## *Outfall Height*

Outfall height was the other limiting factor for fish passage in the structures studied. Research conducted on anadromous species indicated that most adult fish can negotiate rather high outfall heights (around 30 cm), but the limited research done for the nonanadromous resident trout species revealed that much lower outlet heights can completely impede passage, especially for smaller juvenile fish. At least two of the six culverts studied had outlet heights that would be difficult to maneuver for smaller resident trout species (Figure 4). There are two primary causes of perching of the outlet of a culvert: high flow velocity and placing the culvert barrel at an angle that is less than that of the streambed. According to Votapka (1991), assuming the culvert is properly countersunk, the outlet pool immediately beyond the culvert outlet will scour if the flow velocity exceeds approximately three meters/second.



**Figure 4. Perched outfall restricting passage.**

## **Problem Avoidance**

Based on previous research reviewed and the findings from this field survey, several items of extreme importance for avoiding passage impedance were identified, as explained below.

Slope, because it affects many of the other important hydraulic parameters of culverts, is probably the most important factor in culvert installation. Much of the previous research was aimed at determining the maximum slope at which culverts could avoid impedance. However, because flow velocity, depth of flow and outfall heights are

affected by slope, in combination with many other factors, no specific maximum slope is recommended unless all other variables are held constant as well. Since these variables will obviously change from site to site, the results of this study indicate that culverts should be installed at the same gradient as the streambed, provided maximum flow velocity values are not exceeded as calculated by the Manning equation given below.

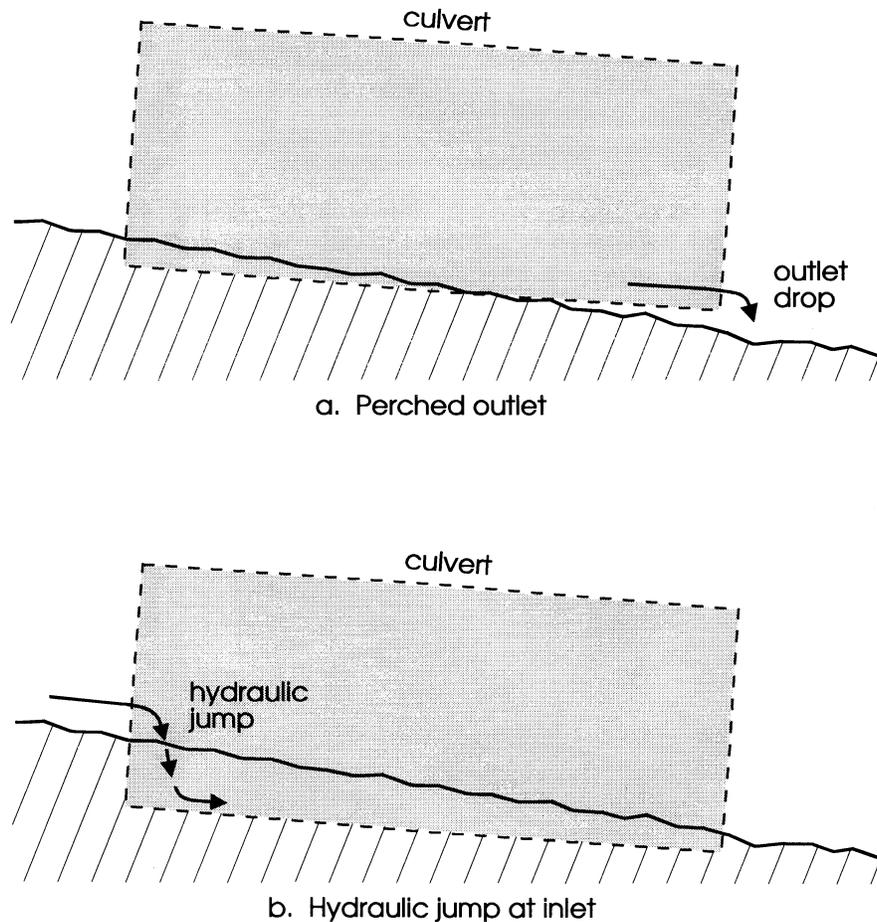
$$V = (1/n)R^{2/3}S^{1/2}$$

where:        V is the average velocity in meters/second  
               R is the hydraulic radius  
               S is the slope of the water surface  
               n is the Manning roughness coefficient  
                  rocky stream beds        = 0.04-0.05  
                  smooth concrete         = 0.012 (Fetter, 1988).

If the culvert is installed at a gradient steeper than that of the streambed, flow in the culvert will accelerate, potentially causing the depth of flow to decrease below minimum values and possibly causing it to become supercritical. If the culvert is placed at a gradient that is less than that of the streambed, as is suggested in some of the literature cited (Baker & Votapka, 1990; Lauman, 1976; Votapka, 1991), then one of two problems may arise: the culvert becomes perched near the outlet if the entire length of the culvert is not countersunk sufficiently (Fig. 5a); or, assuming countersinking of the barrel is sufficient to allow both the reduced slope and the proper depth of the outlet end, a hydraulic jump will exist at the inlet of the barrel (Fig. 5b). A hydraulic jump can cause flow to become turbulent, thereby entraining air, which will result in a reduction of a fish's propulsive power, as well as its buoyancy (Powers, 1992).

For streams which have streambeds with slopes of two to three percent, stream flow velocities will start to approach those that do not allow the passage of nonanadromous trout, unless some type of mechanism is used to slow the flow velocity in the barrel of the culvert. As stated earlier, baffles are not recommended, primarily because they decrease hydraulic capacity, accumulate debris, and require maintenance. However, by increasing the roughness coefficient of the bottom of the culvert, streamflow velocities can be reduced, and the depth of flow in the barrel of the culvert can be increased (Powers, 1992).

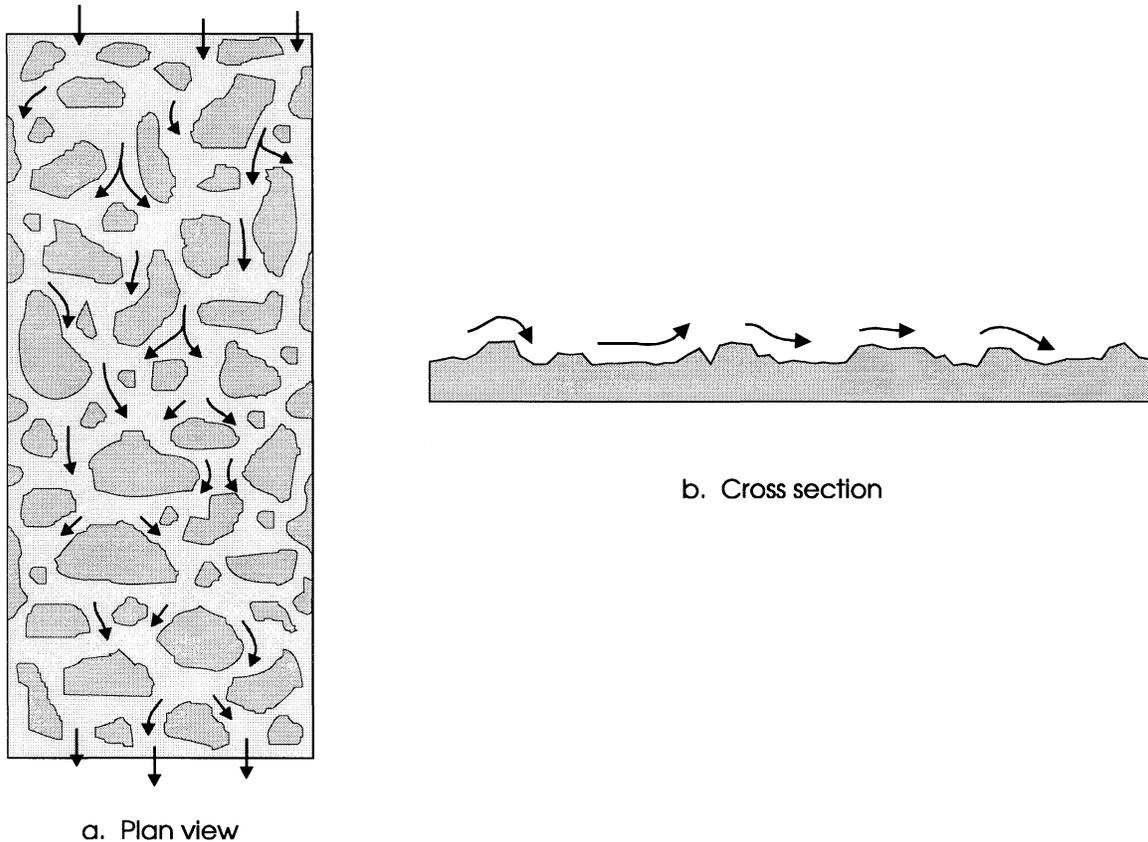
Minimal research has been done on increasing roughness in the bottom of the culvert to decrease flow velocity (Blevins & Carlson, 1988). Wiggert, Erfle, and Morris (1971) experimented with peripheral rings to increase the roughness of circular and square culverts. Reductions in flow velocity of 50 to 70 percent were obtained, depending on slope, flow rate, and ring size. Based on the research of Wiggert et al. (1971) and the field observations made in this study, it is postulated that if the bottom of the culvert could be cast to obtain a roughness coefficient equal to that of the streambed, according to the Manning equation, no increase in flow velocity would occur.



**Figure 5. Problems related to placing culvert barrel at a slope less than that of the streambed.**

Because the undulations and incongruities of this “artificial bottom” would be present the entire length of the culvert, the height of each bump or cobble would not need to be as great as that of the baffles described in the literature. This would limit the hydraulic decreases during periods of high flow and the potential for debris hang-up associated with the typical baffle system.

Figure 6 is a sketch of the artificial bottom. This would potentially solve many of the problems associated with fish passage impedance by culverts, preventing excessive flow velocities, large outfall heights, and shallow depths of flow. The exact design and cost of developing such a bottom in culverts would need further examination. If economically feasible (if it is less expensive than bridge construction and maintenance), artificial bottoms would allow greater use of culverts at stream crossings while not impeding the passage of resident trout.



**Figure 6. Proposed artificial bottom.**

## CONCLUSIONS

- 1) Published maximum flow velocities for anadromous fish are significantly greater than those of Virginia's resident nonanadromous trout species.
- 2) The maximum flow velocity, minimum depth of flow, and maximum outfall height that can be easily maneuvered by Virginia's resident trout species are 1.2 meters/second, 9 cm, and 10 cm respectively. These values are based on the most conservative values found in the literature, and on limited field sampling. All are also dependent on culvert slope.
- 3) Flow velocities in the majority of the culverts observed in southwest Virginia were not the limiting factor for fish passage.
- 4) Outfall heights and shallow depths of flow were the limiting factors for fish passage through most of the sampled culverts in southwest Virginia.

- 5) Increasing the roughness coefficients of culvert bottoms should allow them to be placed in streams with steeper slopes without impeding fish passage.

## **RECOMMENDATIONS**

- 1) Culverts can be considered the primary option for crossing streams that provide habitat for Virginia's resident trout species if the following criteria are met:
  - the culvert can be placed on the same slope as that of the streambed,
  - the slope of the stream is less than three percent,
  - the flow velocity (as calculated using Equation 1) does not exceed 1.2 meters/second under normal flow conditions,
  - the barrel of the culvert can be properly countersunk at the outlet to prevent perching.

Bridges should be used at these crossings if any of the above criteria cannot be met.

- 2) Baffles should not be used to control streamflow velocities in newly installed culverts.
- 3) Concrete aprons should not be used at culvert outlets.
- 4) Additional research should be conducted to develop a culvert bottom design that will have a higher roughness coefficient than standard culvert bottoms. This bottom design should be tested under laboratory conditions to ensure that maximum flow rates are not exceeded when the slope of the culvert barrel is increased beyond three percent. A cost-effective method for fabricating this type of bottom in the field should be researched at the same time.

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