FISH PASSAGE THROUGH CULVERTS IN MONTANA:

A PRELIMINARY INVESTIGATION

by

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16. Abstract

The objective of this report is to combine, in one document, previously reported information on factors influencing fish passage through culverts, especially as it pertains to conditions indicative of Montana. First, the need for considering fish passage is discussed, followed by an investigation of biological, hydrologic and hydraulic criteria influencing fish passage. An integration of biological and hydraulic criteria is presented, as is a review of previous studies conducted in Montana. Recommendations for future research are also presented.

The major biological criteria influencing fish passage are species and size of fish, jumping ability, and seasonal feeding and spawning migrations as related to the hydrologic regime of the stream requiring a culvert crossing. In general, salmonid species and healthy adult fish are the strongest swimmers and spawning is the major reason fish migrate. The main culvert features preventing fish passage include; a perched outlet, too great a velocity, too shallow a depth or too long a distance between resting pools.

The major hydraulic criteria influencing fish passage are: flow rates during fish migration periods; and type, roughness, length and slope of the culvert. In general, the optimum design for peak flow conveyance, a smooth pipe flowing full, will not meet fish passage criteria at any discharge. Fish size appears to have little influence on ability to negotiate a culvert despite its effect on swimming performance. One theory is that smaller fish utilize regions of low velocity near the culvert wall.

Multiple possibilities for future research to better characterize fish passage are listed. Examples include better characterization of velocity gradients within culverts and evaluation of fish swimming performance for poorly characterized Montana species.

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INTRODUCTION

Since passage of the Montana Stream Protection Act of 1965, government agencies in Montana have had to obtain permission from the Montana Department of Fish, Wildlife and Parks (MDFWP) when any construction or maintenance project impacts any stream, its banks, or its tributaries. The Montana Department of Transportation (MDT) is responsible for the maintenance and construction of highways, and over the years, there has been disagreement between the two agencies over the best methods for the design of highway stream crossings. In general, MDT has preferred to use culverts whenever possible because they are easily designed and maintained, can be installed quickly, and are relatively inexpensive as compared to other structures. In general, MDFWP has preferred the use of bridges to minimize the long-term environmental impact to the stream in question. This study was initiated to explore the feasibility of designing culverts for Montana conditions in such a manner as to allow for reasonable passage of fish. The overall goal is to combine biological criteria with hydrologic and hydraulic criteria to design culverts which allow for fish passage as well as providing cost-effective transfer of water under a highway. Criteria necessary to design culverts that pass fish could also be used as a resource management tool to exclude certain undesirable species from moving upstream.

The first task of this study was to determine the design parameters required when designing a culvert to pass fish in Montana. The second task was to collect and review existing reports and define what is known that applies to Montana species and conditions. The final task was to outline the possible courses of action that future research projects could follow.

This paper provides an overview of information regarding fish passage through culverts, describes what is known and unknown, outlines applications to Montana species and conditions and lists possible courses of action for future studies.

BACKGROUND

Fish passage through culverts was not well researched until the passage of many environmental laws by the Federal and State government in the 1960's and 1970's. These laws created a responsibility, on the part of resource managers and engineers, to include environmental considerations in their designs. Environmental concerns, fish passage in particular, have become important design parameters in addition to safety and economics. New culverts must allow fish passage where appropriate, while functioning as a safe and hydraulically adequate structure. In some cases, existing culverts have been successfully retrofitted to allow fish passage.

Culverts may prevent or limit the upstream movement of fish by creating higher flow velocities and/or inadequate flow depths as compared to a natural stream. Fish usually move upstream to spawn, but they also move to feed, hide and find better habitat as conditions in a stream change over time. Downstream movement of fish is not a problem at culvert installations because fish migrating downstream tend to lock into a single velocity streamline and may be swept downstream at a rate well in excess of their normal swimming speed (Bell, 1973).

Fish moving upstream through culverts have to overcome velocities within the pipe as well as the forces of gravity that resist any attempted elevation gain. The efforts put forth by fish attempting to pass upstream through a culvert can be compared to a person trying to ascend a downward-moving escalator. With a certain level of effort a person can match the downward forces due to gravity and the downward velocity of the escalator to maintain a steady position. If effort decreases, the person loses ground and will eventually return to the bottom of the escalator. If the effort put forth is increased slightly, and the escalator is not too long, the person will move upward at a slow pace and will eventually reach the top, or, if the escalator is excessively long, the person will tire and be swept down by the escalator. If the effort is greatly increased, the person will reach the top of the escalator and, having negotiated the escalator, will require a well-deserved chance to rest.

This analogy introduces many of the important variables which influence the ability of a fish to swim through a culvert. Different species and sizes of fish have different swimming abilities just as people of different ages and sizes have varying levels of athletic ability. Healthy adult fish swim more strongly than juvenile fish and can pass upstream through a culvert with less difficulty, just as a healthy adult person can ascend a downward-moving escalator more easily than a young child. If the culvert is too long, a fish may become exhausted while attempting to swim all the way through, just as a long escalator may wear a person down. If the culvert or escalator is too steep, the fish or person may not be able to overcome the down-gradient forces and will be swept to the bottom. If the velocity of water in the culvert is too great, a fish will not be able to swim fast enough to overcome it, just as a person may not be able to run fast enough to overcome the speed of a fast-moving escalator.

As demonstrated above, design of culverts to pass fish requires the integration of two dissimilar sets of criteria: biological and hydraulic. This report provides the reader with information regarding these two criteria.

BIOLOGICAL CONSIDERATIONS

In general, a culvert should be designed to provide passage for a critical species and size of fish during a specific time period. A conservative design would dictate using a stream's weakest swimming species and size of fish that move upstream.

Migration of spawning fish is the most likely reason (but definitely not the only reason) a culvert would need to be designed for fish passage. If a sexually active fish is delayed or prevented from moving upstream to spawn, its eggs may be resorbed or deposited in undesirable habitat downstream from the culvert. The eggs may then be washed away, eaten, ruined by improper temperature or inadequate water levels, or buried in silt (Watts, 1974). Figure 1 is a table compiled from data of Brown (1971) and Holton (1990) showing approximate spawning age, size, and period for some Montana species. Figure 2 shows spawning periods for different species as compiled by Baker and Votapka (1990). These figures provide guidelines for the time of year fish passage is most critical, when spawning is the main concern at a potential culvert location.

It is conceivable that if a threatened or endangered species is involved, the isolation of upstream spawning habitat may significantly reduce the chance for species survival. Some species in Montana that are of special concern are: the pallid and white sturgeons; paddlefish; northern redbelly dace x finescale dace hybrid; pearl dace; sicklefin and sturgeon chubs; westslope and yellowstone cutthroat trout; bull trout; arctic grayling; and the shorthead and spoonhead sculpin (Holton, 1990). Not all of these species are found in every stream; local fisheries biologists should be contacted to determine the areas where these species are found.

Spawning is not the only reason that culverts should be designed to allow upstream fish passage. Most fish thrive within a narrow range of water temperatures; as water temperature in streams change throughout the year, fish may swim upstream or downstream in search of more

Fish Species in Montana	Other Names Names	Approx. Age to Sexual Maturity in Montana	Approx. Size at Sexual Maturity in Montana	Approximate Spawning Period in Montana	Approx. Time for Eggs to Hatch
artic grayling	montana grayling	2 years	9 inches	late march - early june	11 - 22 days
bass, largemouth	largemouth black bass	3 - 5 years	5.5 - 10 inches	May - Mid-July	
bass, smallmouth	smallmouth black bass	4 years	10 inches	May - June	
brook stickleback		2 years	2 inches	May - June	8 days
burbot	ling	3 years	12 inches	winter	30 days
carp		2 - 3 years	10 - 15 inches	May - July	12 - 20 days
channel catfish	channel cat	3 years	10 inches	May - July	6 - 10 days
crappie, black		2 - 3 years	6 - 8 inches	May - June	
crappie, white		2 years	4 inches		
dace, finescsale		1 year	1.8 - 2.2 inches	May - August	8 - 10 days
dace, longnose		3 years	2.8 inches	late spring - early summer	
dace, northern redbelly		1 year	1.8 - 2.2 inches	May - August	8 - 10 days
dace, pearl		2 years	3 - 4 inches	spring	
goldeye	skipjack, shiner, shad	3 - 4 years	12 inches	late March - May	
kokanee	kokanee salmon, silver	4 years	12 inches	November - December	110 days
lake whitefish		2 - 5 years	9 - 16 inches	October - January	
mountain whitefish	rocky mountain whitefish	3 years	11 inches	fall	
northern pike	pike, northern, jack	2 - 3 years	15 - 18 inches	March - May	2 weeks
northern squawfish		5 - 6 years	7 inches+	May - July	
paddlefish	spoonbill cat	5 -15 years	40 - 55 inches	June - August	7 days
peamouth		3 - 4 years	6.5 - 8.5 inches	May - June	
sauger	sand pike	3 - 4 years	9 - 12 inches	April - May	12 - 18 days
stonecat				June - August	1 - 2 weeks
sturgeon, pallid		3 - 4 years	18 - 22 inches	June - July	
sturgeon, shovelnose		3 - 5 years	14 inches+	May - July	1 week
sturgeon, white		10 - 15 years	45 - 60 inches	May - July	1 - 2 weeks
sucker, blue		2 - 3 years	13 - 17 inches	April - June	
sucker, largescale	coarsescale sucker	4 - 5 years	7.5 - 10 inches	April - May	2 weeks
sucker, longnose	finescale sucker	4 - 5 years	10 - 14 inches	April - early July	10 - 20 days
sucker, mountain		2 - 5 years	5 - 7 years	June - July	
sucker, white	common sucker	3 - 4 years	9 - 11.5 inches	April - June	12 - 20 days
trout, brook	eastern brook trout	2 years	6 inches	September - October	5 - 6 months
trout, brown	german brown trout	2 - 5 years	8 - 16 inches	October - December	50 days
trout, bull	dolly varden	4 - 5 years	11 - 14 inches	September - November	5 - 6 months
trout, golden		3 - 4 years	15 inches	June - July	28 days
trout, lake	mackinaw trout			October - November	50 days
trout, rainbow	silver	2 - 3 years	8 - 11 inches	April - July	50 days
trout, westslope cutthroat		3 - 4 years	8 - 10 inches	April - July	
trout, yellowstone cutthroat		3 - 4 years	8 - 10 inches	April - July	
utah chub		3 -4 years	6 - 8 inches	May - July	6 - 9 days
walleye	walleyed pike	2 - 4 years	9 - 16 inches	spring	12 - 18 days
yellow perch	perch	2 years	4 inches	April - May	10 - 20 days

Figure 1: Typical spawning characteristics for fish found in Montana. Data from Brown (1971) and Holton (1990).

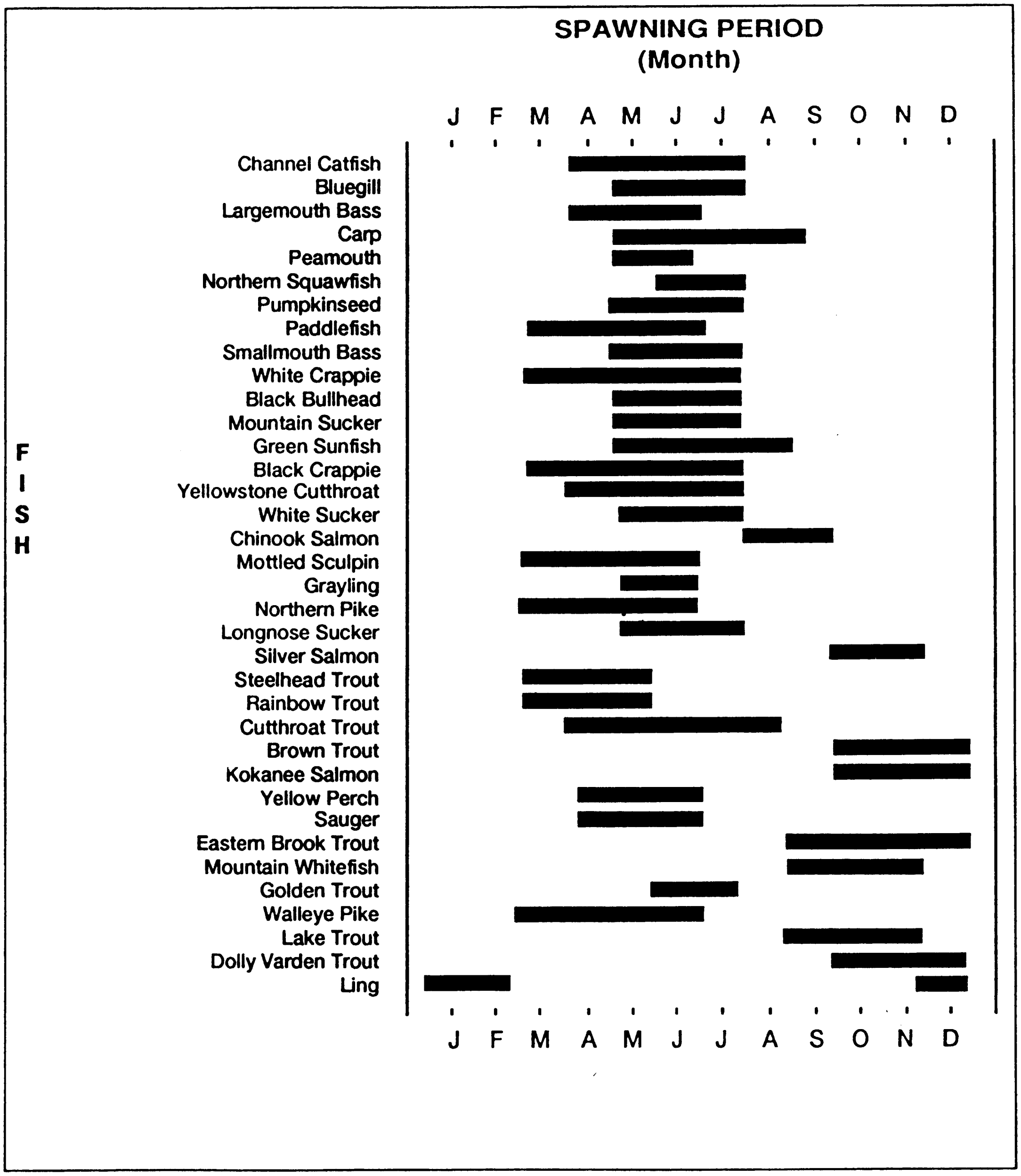


Figure 2: Spawning periods for different species of fish, some of which are found in Montana. From Baker and Votapka (1990).

favorable temperatures. Fish may also move upstream or downstream to feed. For example, annual aquatic insect hatches provide an accessible and plentiful food source for fish. These hatches are often a function of water temperature; as a portion of a stream approaches a given temperature the insects emerge and fish will move to that stream reach and feed.

Perennial streams are not the only concern. Ephemeral or intermittent streams can be important spawning or feeding tributaries to larger rivers or lakes. There are well-documented cases in Montana where streams that are dry several months a year support nonmigratory resident fish species in the large, still pools that remain throughout the year (Guzevich, 1993).

The designer may need to be concerned with all species of fish in the system, and not just the popular game species. For example, there is one case where the dace, a 50 mm (2 inch) long fish was present in a central Montana stream and a proposed culvert design was modified to accommodate passage of this non-game species.

SWIMMING ABILITY

The "Fisheries Handbook of Engineering Requirements and Biological Criteria" by Bell (1973) is one of the most well known documents on the swimming ability of fish. Though this report is more than 20 years old, it is still the best assemblage of swimming speed data as a function of species. According to Bell (1973), fish have three swimming speeds: **cruising**, which can be maintained indefinitely; **sustained**, which can be maintained only for a few minutes; and **darting**, which can be maintained for only 5 to 10 seconds. Figure 3 contains the "relative swimming speeds of adult fish" table compiled by Bell (1973), and Figure 4 contains the numerical version of Bell's data as compiled by Watts (1974). Figure 5 (Watts, 1974) provides reported values for **maximum** swimming speeds of fish. Analysis of these tables clearly shows that salmonids (trout, salmon, grayling, char and whitefish) tend to be the strongest swimmers.

Fish maintain various speeds by utilizing two general types of muscle with very different metabolisms. Red muscle is aerobic and is used for the longer duration cruising and sustained speeds. White muscle is anaerobic in nature and is used for very short duration darting speed. White muscle provides highly elevated levels of swimming power for very short periods of time (Bell, 1973; Behlke et al., 1991). Red muscle needs little or no recovery time after use; enough oxygen is constantly moving through the gills to keep the muscle adequately supplied. After white muscle

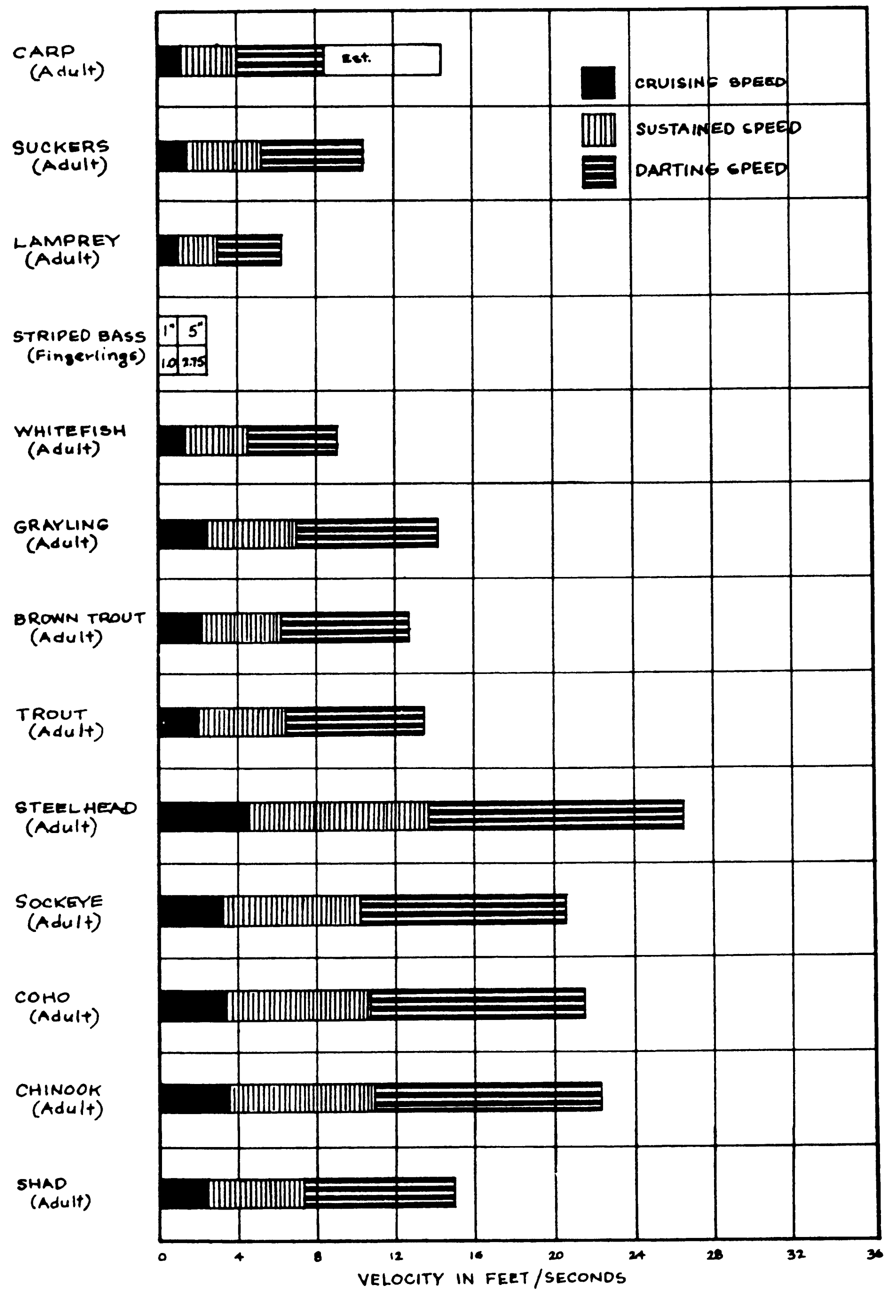


Figure 3: Relative swimming speeds of average sized adult fish. From Bell (1973).

Specie	Cruising speed fps	Sustained speed fps	Darting speed fps
Carp	0 to 1.2	1.2 to 4.0	4.0 to 8.4
Suckers	0 to 1.4	1.4 to 5.2	5.2 to 10.3
Lamprey	0 to 1.0	1.0 to 3.0	3.0 to 6.3
Whitefish	0 to 1.3	1.3 to 4.4	4.4 to 9.0
Grayling	0 to 2.5	2.5 to 7.0	7.0 to 14.2
Brown trout	0 to 2.2	2.2 to 6.2	6.2 to 12.7
Trout	0 to 2.0	2.0 to 6.4	6.4 to 13.5
Steelhead	0 to 4.6	4.6 to 13.7	13.7 to 26.5
Sockeye	0.to 3.2	3.2 to 10.2	10.2 to 20.6
Coho	0 to 3.4	3.4 to 10.6	10.6 to 21.5
Chinook	0 to 3.4	3.4 to 10.8	10.8 to 22.4
Shad	0 to 2.4	2.4 to 7.3	7.3 to 15

Figure 4: Relative swimming speeds of average sized adult fish. From Watts (1974).

Species	Max fps	Experimenter
Brown trout	12.8	Kreitmann (1933)
Brown trout	5.6	Schmassmann (1928)
Brown trout	7.1	Hydrotechnical Research Ins of Leningrad
Sea trout	8.4	Kreitmann (1933)
Sea trout	6.4	Schmassmann (1928)
Sea trout	7.1	H R I of Leningrad
Atlantic salmon	8.4	Kreitmann (1928)
Atlantic salmon	6.4	Schmassmann (1928)
Atlantic salmon	26.5	H R I of Leningrad
Atlantic salmon	12.5	as above but in large numbers
Atlantic salmon	7.8-9.3	H R I of Leningrad
Steelhead	12.0	Paulik and DeLacy (1957)
Steelhead	26.7	Collins and Elling (1960)
Steelhead	26.8	Weaver (1963)
King salmon	14.5	Paulik and Delacy (1957)
King salmon	22.1	Collins and Elling (1960)
King salmon	21.9	Weaver (1963)
Silver salmon	12.2	Paulik and DeLacy (1957)
Silver salmon	17.5	Weaver (1963)
Red salmon	10.3	Paulik and Delacy (1957)
Trout	11.4	Denil (1938)
Grayling	7.1	H R I of Leningrad
Whitefish	4.6	same
Lamprey	6.2	same
Carp	1.2	Kreitmann (1933)
Tench	1.5	same
Pike	1.4	same
Skipjack tuna	19.2	Comm Fish Review (1964)
Yellowfin tuna	16.7	same

Figure 5: Maximum swimming speeds of adult fish. From Watts (1974).

is used, a fish needs a rest period before it is able to use that mode of propulsion again (Behlke et al., 1991).

Fish swimming performance can be affected by several other factors which are difficult to quantify. Up to a 50% reduction in swimming performance can be expected at the high and low extremes of survivable temperatures (Bell, 1973). For instance, it was found that adult salmon swim strongest when the water temperature is between 18 and 21 degrees C (65 and 70 F), while the weakest swimming occurs above 24 degrees C (75 F) and between 0 and 4 degrees C (32 and 40 F) (Metsker, 1970). Metsker (1970) notes that, in some species, the swimming ability of younger fish tends to be less affected by fluctuations in temperature.

A shortage of dissolved oxygen in the stream also reduces swimming performance. Dissolved oxygen is reduced by introductions of sewage and other organic waste. In one study, a reduction of dissolved oxygen content from 7 p.p.m. to 3 p.p.m. substantially reduced the sustained swimming speeds of fish (Metsker, 1970).

It is important to note that many species of fish travel tens or hundreds of miles during the spawning season. Typically, their swimming ability decreases as distance traveled increases. Culvert flow conditions that a fish could have negotiated during the early part of its migration may be impassable near the end (Watts, 1974). Powers and Orsborn (1985) recommended reducing the maximum, or burst speeds of a fish by a coefficient of condition (Cfc) to reflect the condition of the fish. For fish fresh and ready to begin a migration, Cfc would be 1.0. For fish in good condition and partially through with a migration, Cfc would be 0.75, and for fish in poor condition and nearly done with their migration, Cfc would equal 0.50.

Nearly all of the literature consulted pertained to the swimming ability of salmonids, and none addressed in detail, the fluvial swimming or jumping ability of some species occurring in eastern Montana such as walleye and northern pike. As mentioned earlier, previous studies have shown that the strongest fluvial swimmers are the salmonids, while walleye and northern pike are known to be weaker swimmers. Northern pike prefer a slow moving or zero velocity setting with lots of vegetation and rarely seek out moving water. They are among the weakest swimmers when subjected to fluvial conditions, and therefore poorly equipped to negotiate culverts placed in streams.

Even though they prefer still water, there are resident populations of northern pike in some Montana streams and rivers, including the lower Flathead River in northwestern Montana (DosSantos, 1991) and Beaver and Little Beaver Creeks in southeastern Montana (Guzevich, 1993). Some radio tagged northern pike in the lower Flathead River have traveled almost 18 kilometers (11 miles) upstream over the course of 27 days during the spring and early summer spawning run (DosSantos, 1991). Their presence in the Flathead River is made possible by the large size of this river and rapid water level fluctuations in the channel due to the operation of Hungry Horse Dam. These factors combine to create large zones of very slow velocity backwater and slough areas near the edges of the river that allow pike to move upstream with minimal effort.

IMPACT OF FISH SIZE ON SWIMMING ABILITY

Fish size affects swimming ability. Younger and smaller fish do not swim as strongly as healthy adult fish of the same species. Studies done on Arctic grayling in Alaska have shown that the power required to propel a fish through the water is proportional to the length of fish raised to the 1.8 power, while the propulsion power available within the red muscle (used for cruising and sustained speeds) is proportional to the length of fish raised to the 2.34 power (Behlke, 1991). It is apparent that the power available increases more rapidly than the power required for propulsion as the length of fish increases; in other words, larger fish can generate more surplus power and swim faster than smaller fish of the same species. This allows the healthy adult fish to negotiate areas of higher velocity more easily than sub-adult fish. Watts (1974) developed the graph in Figure 6 that relates sub-adult swimming ability to adult swimming speeds using data compiled by Bell (1973). Figure 7 is from Baker and Votapka (1990) and shows relative swimming abilities as a function of fish species and length.

Interestingly, Belford's (1986) field research at six Montana culvert sites showed no correlation between fish length and ability to swim through a culvert. He attributed this to smaller fish being able to take better advantage of the low velocities found near corrugated culvert walls, while acknowledging that larger fish have stronger absolute swimming ability. Behlke et al. (1991) suggests that smaller fish also have less drag and gravity forces to overcome than large fish, which may help them negotiate some culverts. Figure 8 shows a typical velocity profile for baffled and unbaffled culverts, and clearly shows the zones of low velocity near the culvert walls.

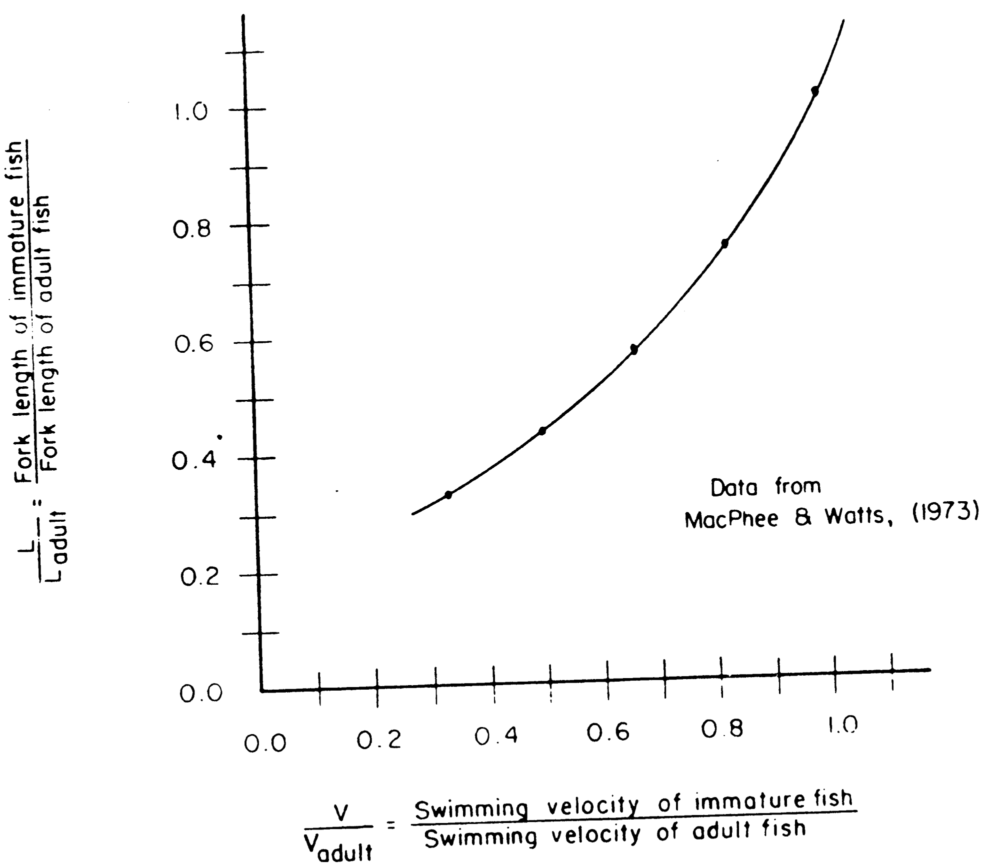


Figure 6: Relative swimming speed versus relative length of fish. From Watts (1974).

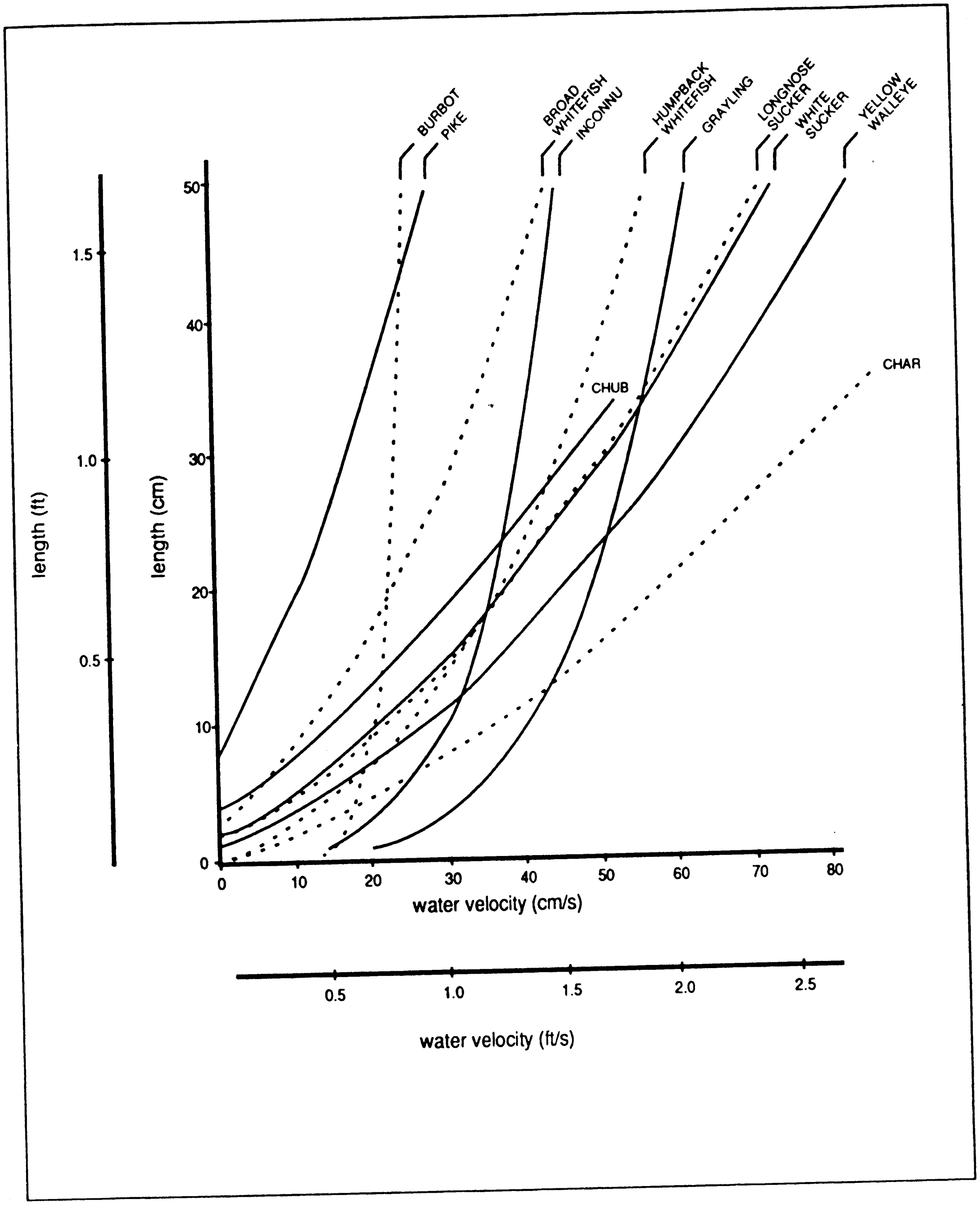


Figure 7: Relationship between length of fish and ability to move 100 meters in 10 minutes in water velocities up to 80 cm/sec for fish from the MacKenzie River in Canada. From Baker and Votapka (1990).

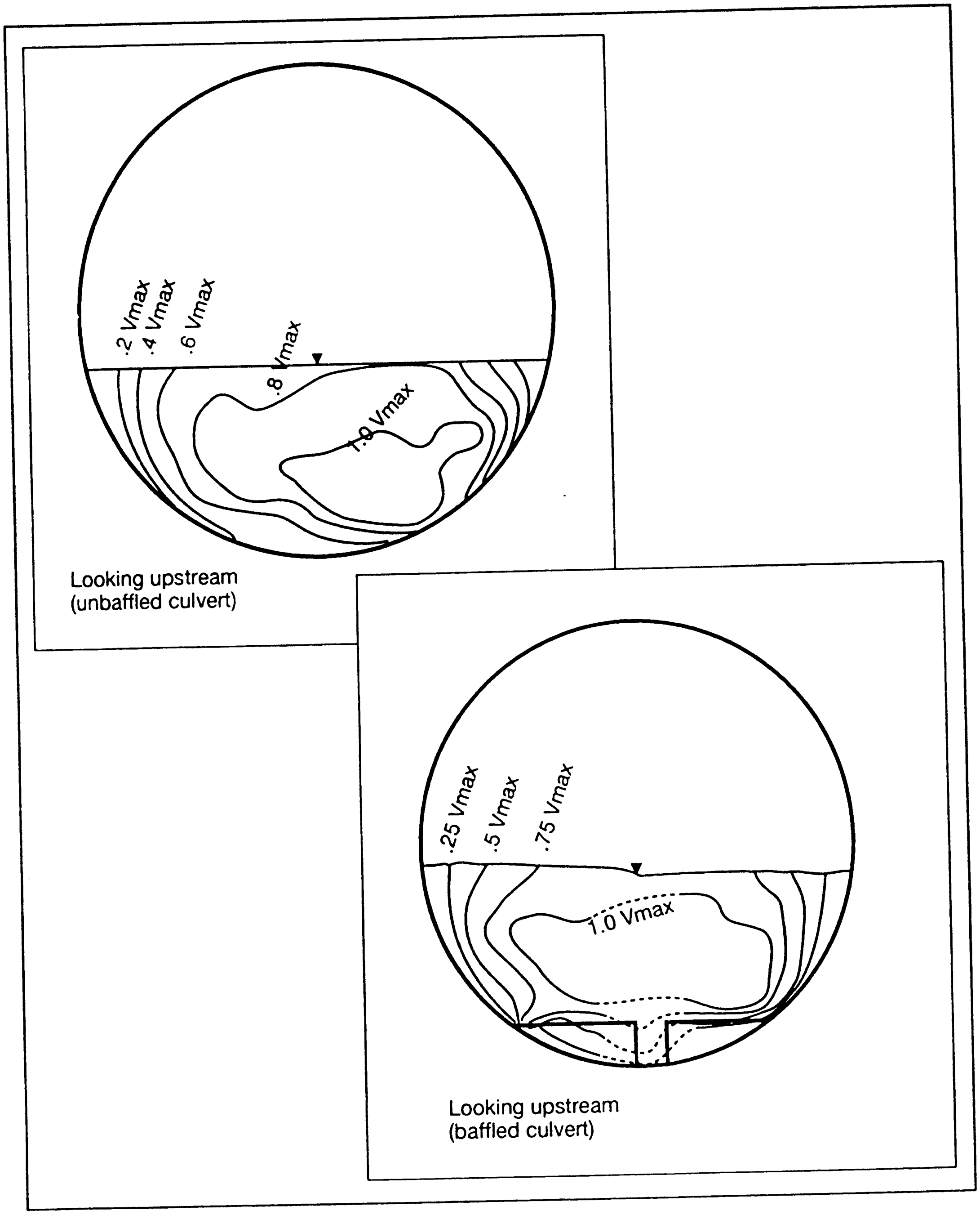


Figure 8: Typical velocity profiles for unbaffled and baffled round culverts, with velocities expressed as a fraction of the maximum flow velocity. From Baker and Votapka (1990).

SWIMMING ABILITY AS RELATED TO CULVERT LENGTH AND SLOPE

The length of culvert and its relation to how long a fish can maintain a certain speed is a major design consideration. Obviously, a higher flow velocity in the culvert means a fish must swim faster to pass through. In general, flow velocity increases with increases in discharge and culvert slope, and decreases with increases in culvert wall roughness and culvert size.

Fish are able to negotiate short culverts with relatively high flow velocities, but for passage through longer culverts, the allowable flow velocity is much less. For example, a 33 cm (13 inch) long fish was found to pass a 9 meter (30 ft) long culvert that had a flow velocity of 150 cm/sec (5 ft/sec), but the same fish could only pass a 15 meter (49 ft) culvert if the flow velocity was 30 cm/sec (1 ft/sec), (Jones et al., 1974). Watts (1974) recommends using the higher end of the range of sustained swimming speeds shown in Figures 3 and 4 for culverts up to 18 meters (60 ft) long, and using the slower end of the range of sustained speeds for culverts approaching 46 meters (150 ft) in length. Longer culverts may require that an even slower estimated swimming speed be used in design.

Studies done in Alaska showed that Arctic grayling maintain a net ground speed of approximately 0.3 m/sec (1 ft/sec) regardless of stream velocity when negotiating obstacles (Behlke, 1991). Bell (1973) mentions that fish can sense variations in water velocity as small as 0.03 m/sec (0.1 ft/sec) and they tend to adjust their swimming speeds in order to maintain a relatively constant ground speed. Fish tend to swim along one streamline unless an obstacle is encountered (Bell, 1973). As soon as an obstacle is encountered, however, fish tend to move away from the paths of lowest velocity into the areas of higher velocity. One explanation for this is that migrating fish probably sense that the areas of lowest velocity may not lead upstream, and that the low velocity may be the result of an impassable obstacle.

JUMPING ABILITY OF FISH

It is sometimes necessary for fish to jump to enter a culvert or to pass some obstruction within or near a culvert. Stuart (1962) performed a variety of tests on salmon and trout jumping abilities utilizing a 15.2 meter (50 ft) long flume in which different manmade weir shapes and obstacles could be placed. Fish tended to leave the downstream pool of water at an angle of 45 degrees as they jumped, completely clearing the nappe of water flowing over the weir. It was also observed that the jumping fish almost always landed on the crest of the nappe at an angle of 8 to 10 degrees from the horizontal. In his study, Stuart (1962) found that the fish never "missed" a jump over a manmade obstacle once they left the water and that they never cleared the crest of any manmade weir by more than one inch. It was common, however, for a fish to make many attempts at jumping only to abort the attempt just prior to take off. When the obstacles were more natural, and presented less-uniform flow conditions, the rate of successful jumps dropped somewhat, but failed jumps were still rare.

Powers and Orsborn (1985) studied the jumping behavior of coho salmon and chum salmon, two closely related species. It was found that coho salmon usually leapt over obstacles if they could not swim past an obstacle on the first attempt. Chum salmon repeatedly tried to swim past obstacles, rarely choosing to leap. This illustrates the variability of behavior possible in two very similar species for which the designer and biologist must be aware before attempting to design a culvert for fish passage. A culvert designed for fish passage should not create hydraulic conditions that force a fish to jump in order to enter into or pass through the culvert.

<u>OTHER BIOLOGICAL CONCERNS</u>

Some species of fish move primarily at night while other species may move between dawn and early afternoon (Watts, 1974). The light and dark contrasts at culverts during daylight hours did not appear to have a significant impact on the movement of some fish through culverts; trout and related species moved into and out of culverts apparently unaffected by the darkness within the pipe. Even so, Bell, (1973) and Watts, (1974) recommended minimizing any sharp light/dark contrast near the openings of a culvert. Belford, 1986, found that darkness within culverts had no impact on the daytime movement of four species of Montana trout through culverts. Local fisheries biologists might be able to furnish detailed information on the light preferences of individual species.

Some fish can withstand delays in their upstream movements without harmful effects. For example, arctic grayling in Alaska migrate during the annual spring-runoff flow and they can withstand a two-day delay in their migration; in other words they can be delayed at a culvert or other obstacles for up to two days while they wait for hydraulic conditions permitting passage (Behlke et al., 1991).

HYDRAULIC CONSIDERATIONS

The primary function of any culvert is to carry water from a stream or manmade channel under an embankment or other feature. Culverts are usually designed to convey peak flows, with a majority of the culvert's cross-section remaining empty most of the time. Following is a discussion of the hydrologic and hydraulic criteria that are followed when designing a culvert to pass fish.

HYDROLOGIC ANALYSIS

Culverts placed in streams are usually designed to safely (without damage) convey a flood that has a low probability of occurrence (low frequency). For example, a flood with a 50-year recurrence interval has a 1 in 50 chance of occurring in any given year, for a 2% probability of occurrence. Design flood frequency for highway drainage facilities is usually determined by an economic balance; in general, a larger drainage structure will be able to pass larger flows without damage, but has higher initial costs than a smaller structure. Therefore, traditional design has attempted to minimize culvert size for a certain predefined level of risk.

Culvert size can be minimized by increasing the hydraulic efficiency. This can be done by using a culvert with smooth interior walls, or encouraging the culvert to flow full with high flow velocities. Unfortunately, the characteristics of a hydraulically efficient culvert are almost always the antithesis to maximizing fish passage efficiency.

Behlke et al. (1991) suggests that the hydrologic study must determine the mean flow rate of the season in which the stream's fish run(s) occur. The hydrologic study must also take into account the delays that a fish population can withstand in their upstream movements without harmful effects. For example, the aforementioned arctic grayling in Alaska migrate during the annual spring-runoff flow and they can withstand a two-day delay in their migration (Behlke et al., 1991). Figure 9 is a sample hydrograph showing the reduced fish passage flow plotted on the mean-annual spring-runoff flood (Behlke et al., 1991). Figure 10 (Montana Department of Transportation, 1995) provides a list of Montana-specific low-flow estimating publications that could be utilized if a detailed hydrograph analysis is not performed.

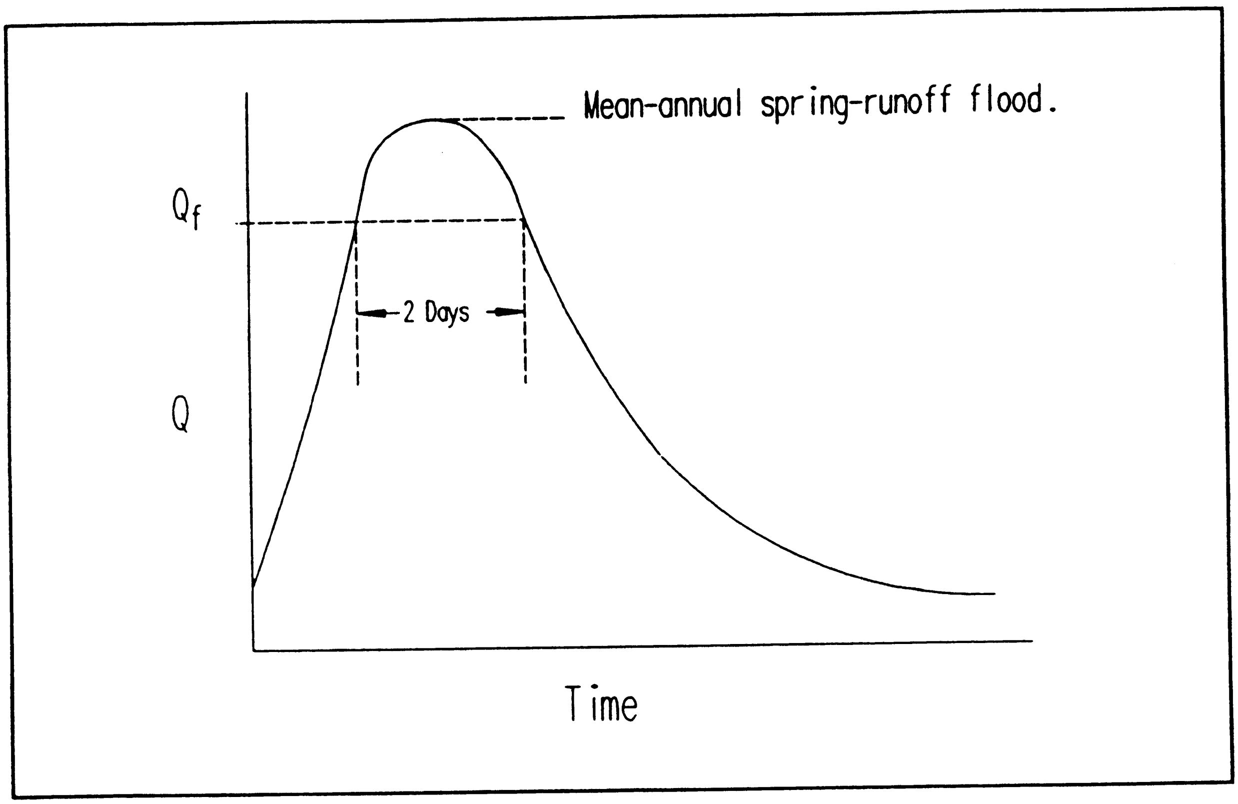


Figure 9: Sample hydrograph indicating reduced fish passage design flow (Q_f) resulting from a 2-day delay allowance for grayling during a spring runoff flood. From Behlke et al. (1991).

• A Method for Estimating Mean Annual Runoff of Ungaged Streams Based on Basin Characteristics in Central and Eastern Montana, USGS Water Resources Investigations Report 84-4143, 1984. Provides three methods for estimating mean annual flow. Prepared in cooperation with the U.S. Bureau of Land Management. Applicable to central and eastern Montana, approximately east of 110° longitude.

• Mean Annual Runoff and Peak Flow Estimates Based on Channel Geometry of Streams in Northeastern and Western Montana, USGS Water Resources Investigations Report 83-4046, 1983. Provides two methods for estimating mean annual flow and peak discharges. Prepared in cooperations with the U.S. Bureau of Land Management, U.S. Forest Service and Montana Department of Natural Resources and Conservation. Applicable to western and northeastern Montana.

• Mean Annual Runoff and Peak Flow Estimates Based on Channel Geometry of Streams in Southeastern Montana, USGS Water Resources Investigations Report 82-4092, 1983. Provides two methods for estimating mean annual flow and peak discharges. Prepared in cooperation with the U.S. Bureau of Land Management. Applicable to southeastern Montana.

• A Procedure for Estimating Flow-Duration Curves for Ungaged Mountainous and High Plains Streams in Montana, by A.B. Cunningham and D.A. Peterson, Department of Civil Engineering, Montana State University, June 1983. Provides one method for estimating flow-durations curves for ungaged, continuously flowing streams (not applicable to ephemeral streams). Prepared for The U.S. Office of Water Research and Technology, Montana Department of Natural Resources and Conservation, Montana Department of Fish, Wildlife and Parks, and Foundation for Montana Trout. Applicable to all portions of the state, on perennial streams.

• Streamflow Characteristics of the Upper Columbia River Basin, Montana, Through September 1979, USGS Water Resources Investigations 81-82, 1982. Provides gaging station data for annual low flow and annual high flow periods. No estimating techniques presented for ungaged streams. Prepared in cooperation with the Montana Department of Natural Resources and Conservation. Applicable to gaging stations in the Columbia River drainage basin in Montana.

• Methods for Estimating Monthly Streamflow Characteristics at Ungaged Sites in Western Montana, USGS Water Supply Paper 2365, 1990. Provides three methods for estimating mean monthly discharge and 90, 70, 50, and 10 percent exceedance values for each month. Prepared in cooperation with BIA and CS&K Tribes. Applicable to Montana west of the Continental Divide.

• Estimates of Monthly Streamflow Characteristics at Selected Sites in the Upper Missouri River Basin, Montana, Base Period Water Years 1937-1986, USGS Water Resources Investigation Report 89-4082, 1989. Provides three methods for estimating mean monthly and 90, 80, 50 and 20 percent exceedance values for each month. Prepared in cooperation with Montana Department of Fish, Wildlife and Parks. Applicable to the Missouri River basin above Fort Peck Dam.

• Estimates of Monthly Streamflow Characteristics for Selected Sites in the Musselshell River Basin, Montana, Base Period Water Years 1937-86, USGS Water Resources Investigation Report 89-4165, 1989. Provides four methods for estimating mean monthly values. Prepared in cooperation with Lower Musselshell Conservation District and Montana Department of Natural Resources and Conservation.

• A Method for Estimating Mean and Low Flows of Streams in National Forests of Montana, USGS Water Resources Investigations Report 85-4071, 1985. Provides three methods for estimating mean annual discharge, and one method for estimating 95 percent and 80 percent annual exceedance values. Prepared in cooperation with Montana Reserved Water Rights Compact Commission and U.S. Department of Agriculture, Forest Service. Applicable to national forest lands west of longitude 109°.

• Streamflow Characteristics of the Yellowstone River Basin, Montana, Through September 1982, USGS Water Resources Investigations Report 84-4063, 1984. Provides gaging station data for annual low flow and annual high flow periods. No estimating techniques presented for ungaged streams. Prepared in cooperation with the U.S. Bureau of Land Management. Applicable to gaging stations in the Yellowstone River basin.

Figure 10: List of publications available for estimating design flows for fish passage. Compiled by the Montana Department of Transportation (1995).

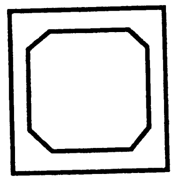
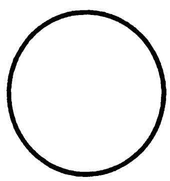
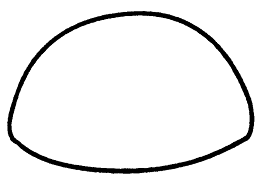
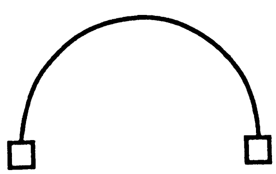
SHAPE	CHARACTERISTICS
 BOX (Square)	– WIDE BOTTOM AREA; BACKWATER INFLUENCE IS GREATER THAN FOR CIRCULAR OR ELLIPTICAL SHAPES. – CAN BE PLACED SIDE BY SIDE TO MAXIMIZE END AREA. – BAFFLE DESIGN AND CONSTRUCTION SIMPLIFIED.
 CIRCULAR	– DEPTH OF WATER AT LOWER DISCHARGES IS GREATER THAN THAT OF OTHER COMMON SHAPES, IMPROVING FISH ACCESS DURING LOW FLOWS. – INFLUENCE OF BAFFLES ON CULVERT HYDRAULICS IS REDUCED.
 PIPE ARCH	– WIDE BOTTOM AREA; BACKWATER INFLUENCE IS GREATER THAN FOR CIRCULAR OR ELLIPTICAL SHAPES. – LOW PROFILE; ADVANTAGEOUS FOR SITUATIONS IN WHICH HEADROOM IS LIMITED OR UPSTREAM WATER STAGE MUST BE MINIMIZED.
 ARCH	– PERMITS STREAM SUBSTRATE TO BE RETAINED WITHIN THE CULVERT AND APPROXIMATES THE NATURAL CONDITIONS WITHIN THE NATURAL CHANNEL.

Figure 11: Common culvert shapes. From Baker and Votapka (1990).

CULVERT SHAPE AND MATERIAL

Once the fish passage discharges have been determined, the designer can begin selection of a culvert. Culvert shape and wall material both influence fish passage. Culvert shapes include circular pipes, arch (squash) pipes, elliptical pipes, rectangular box culverts and open-bottomed arches. Figure 11 shows the common culvert shapes. The most commonly used culvert shape (and the least expensive) is circular and the least commonly used culvert shape (and the most expensive) is the open-bottomed arch.

Circular culverts are easy to install and they are relatively inexpensive. The depth of flow at low discharges is usually sufficient for fish passage, but flow velocities may be excessive due to the low cross-sectional flow area.

Arch (squash) pipes and elliptical culverts are used in areas where headroom over the pipe is limited. At average or low discharges they provide greater flow area for a given flow depth than circular culverts. The increased flow area allows velocities that may permit fish passage, but the resulting flow depth may be too shallow for fish to pass.

Rectangular box culverts have a wide flow area that reduces headwater depth for a given discharge, but again the wide flow area may result in lower velocities at the expense of adequate flow depth.

Open-bottomed arches mimic the waterway opening of a small bridge; they allow the natural streambed to pass uninterrupted under the embankment. It is easier for fish to pass a natural streambed than the inside of a closed culvert because the roughness of a natural streambed is quite variable, creating pockets of low velocity. These structures require expensive preformed or cast-in-place footings to support the soil and live loads. The footings must also be designed to resist streambed scouring. Footings are not necessary with the other culvert shapes, (Baker and Votapka, 1990).

The most common culvert materials are corrugated steel and reinforced concrete, but culverts can also be made of corrugated aluminum, corrugated plastic, smooth plastic, smooth steel, or cast iron. Generally, culverts with corrugated interior walls are preferred to smooth walled culverts because the effective roughness of the corrugations reduces the flow velocity in the zone near the culvert wall; the larger the corrugations, the further the zone of lower velocity tends to extend from the wall (Figure 8). This zone is where fish will swim when negotiating a culvert (Behlke et al., 1991). Smooth walled culverts have a very small zone of reduced velocity which fish are often unable to use (Behlke et al., 1991). The smooth walled culverts such as concrete and smooth plastic have Manning's roughness coefficients which are on the order of 0.012-0.015, while corrugated metal culverts have Manning's roughness coefficients ranging from 0.024 for small corrugations to 0.038 for deep, largely spaced corrugations (Normann, et al, 1985). The higher Manning's roughness coefficients reduce the average flow velocity for a given discharge while increasing flow depth, both of which are desirable for fish passage.

AASHTO's Model Drainage Manual (1991) - Chapter 15 lists, in order of preference, the different types of structures that generally provide the best hydraulic conditions for fish passage.

1) Bridges.

2) Structural plate arch culvert (steel or aluminum).

3) Countersunk corrugated pipe.*

4) Countersunk concrete box culvert or concrete pipe.*

5) Corrugated pipe with a slope less than 0.5%.

6) Corrugated pipe with sills, baffles, etc. on grades between 0.5% and 5.0%.

7) Concrete pipe with sills, baffles, etc. on grades between 0.5% and 5.0%.

*AASHTO defines countersinking a pipe as setting the flowline invert (bottom) at least 0.6 meters (2 feet) below the natural streambed elevation. It is probably more appropriate to consider the depth of countersinking to be some fraction of the culvert diameter rather than a minimum of 0.6 meters (2 feet).

CULVERT DURABILITY: CORROSION, SEDIMENT, DEBRIS AND ICE

Given the types of culvert shapes and materials available, it is necessary to look at the durability of culvert installations. Durability of a culvert can be affected by the corrosiveness of the soil or water, the amount of bedload in a stream, the amount of debris carried in the stream and the type of ice conditions to which the culvert is subjected (Baker and Votapka, 1990).

Corrosion of metal culverts is a major concern. Low pH values and/or high electrical conductivity of soil and water will corrode metal culverts. Most common corrugated steel culverts have a sacrificial galvanized coating which will delay, but not prevent, corrosion of the culvert wall. Other types of coatings which extend steel culvert life include bituminous, polymeric and aluminized (A.I.S.I., 1983). Aluminum culverts tend to be less affected by corrosion and need no protective coating (A.I.S.I., 1983). Concrete culverts are less affected by pH and resistivity, but the strength of concrete in the culvert wall may be reduced in the presence of sulfates.

The bedload size and sediment transport rate in a stream must be considered in design of a culvert. Large rocks moving through a corrugated steel or aluminum culvert can abrade the bottom of the culvert, making a structure prone to failure. Concrete culverts are much more resistant to damage caused by bedload transport. Bedload deposition due to decreased flow velocity at the outlet of a culvert is also a concern, as accumulation of material could become a physical barrier to fish migration.

The accumulation of debris at a culvert inlet can cause water to overtop the embankment, which in turn may cause erosion of the embankment and/or flooding of land upstream from the culvert. Baker and Votapka (1990) point out that more culverts have failed as a result of debris accumulation than as a result of hydraulic inadequacy. The accumulation of debris can reduce the flow velocity immediately upstream of a culvert, inducing deposition of sediments. Debris accumulation may alter the hydraulic flow characteristics, rendering a culvert impassable. Debris may also present a physical barrier that blocks the upstream and downstream movement of fish. Debris can be controlled at a point upstream of the culvert, but debris-control structures require periodic maintenance. An alternate way of managing debris is the use of an overflow pipe that conveys the flow when the primary culvert becomes plugged. The designer may design the culvert to pass debris, but this may result in a structure which is greatly oversized.

Beaver problems should be accounted for in the design process. Beavers are industrious and can render the most well thought-out fish passage culvert impassable in a matter of hours. Failed beaver dams can also be a significant source of debris.

Ice buildup in the wintertime is site dependent, and typically only a fisheries concern in locations where fish passage is required during the winter months (Baker and Votapka, 1990).

Again, an overflow culvert could be used to carry flows should the primary culvert become plugged with ice.

INTEGRATION OF BIOLOGICAL AND HYDRAULIC CRITERIA

Following is a list of common problems that prevent fish passage through culverts:

1) The velocity of water over a given length of culvert may be too great in relation to fish swimming capabilities.

2) Improper depth of water in the culvert during low, moderate, or high discharges.

3) Icing and/or debris problems.

4) Improperly selected design flows in relation to annual hydrograph and the time (season) of fish passage.

5) Failure to account for the correct size and species of fish which need to pass through the culvert.

6) Failure to design for a stream's sediment load.

7) Failure to account for erosion caused by the culvert installation.

Given all of these possible problems, it is recommended that three disciplines be involved if a culvert design is to successfully integrate biological and hydraulic factors in order to pass fish: fisheries biologists, hydrologists and engineers. If only one discipline is involved in the design, fish passage may be compromised, the structure may fail, or the project may be unnecessarily expensive.

The hydrologist and the engineer (sometimes one person is trained in and performs both duties) should cooperate with local fishery biologists to determine which species are present in the system, how large the migrating fish will be and when, during the year, fish passage is a concern. The species is important because different species of fish have different swimming abilities and spawn at different times. Information concerning the size of fish is needed because larger fish tend to swim more strongly than smaller fish of the same species. The timing must be known because the hydrologist must determine what the streamflows will be during the periods of fish movement.

At the Montana Department of Transportation (MDT), the hydraulic engineers assume the role of both hydrologist and engineer, while the fisheries biologists from the Montana Department of Fish, Wildlife and Parks (MDFWP) inform MDT of the species present in the stream. The biologists are asked to furnish estimated spawning periods and fish sizes as they relate to passage requirements.

Any culvert must be designed to meet peak flow criteria as outlined earlier, as well as accommodate fish passage at a flow rate which in all likelihood will be different. If spawning or other seasonal movement is the main concern, flow rates for that time of year must be estimated. It may be that fish passage is a year-round concern if there are resident species that need to move freely up and down stream past the culvert, in which case a moving discharge-versus-critical duration analysis must be performed.

ANALYZING FISH PASSAGE THROUGH CULVERTS

Two methods for analyzing fish passage characteristics through culverts are currently in use: the first will be referred to as "traditional" fish passage design while the second will be referred to as "Alaskan" fish passage design.

The traditional approach is empirically based and has been continually refined since the early 1960's. This method is fairly easy to use; the swimming ability of the "design fish" is determined from methods previously discussed, and the culvert must provide flow velocities and depths that allow the fish to move through the culvert without substantial delay.

The Alaskan approach has been developed over the last decade and uses derived equations for the different forces acting on a fish: drag, thrust, weight, buoyancy and down-gradient forces as shown in Figure 12 (Behlke et al., 1991). This method calculates swimming power and energy required for propulsion and compares them to the energy and power available within a fish's muscle mass. Consideration of where within the culvert fish swim is made instead of simply utilizing the average flow characteristics. While solidly based in the theories of biomechanics, physics and hydraulics, field testing has been limited. Also, this method is more difficult to apply than the traditional method and is hard to calibrate for different species. The original model was calibrated using arctic grayling.

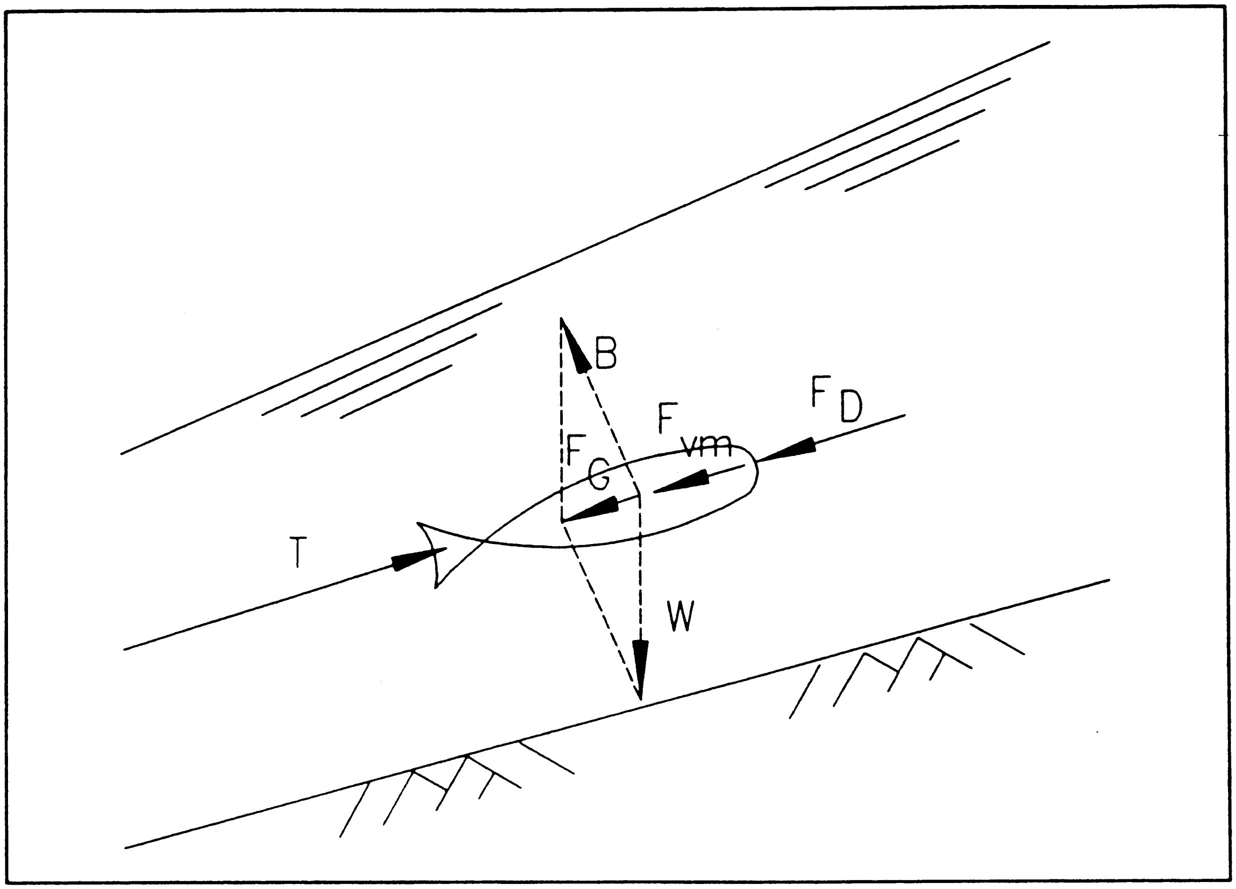


Figure 12: Forces acting on a swimming fish. The vector sum of the fish weight (W) and the buoyant force (B) is the down-gradient force (F_G). Thrust force (T) is propulsive force developed by the fish. The fish must overcome a drag force (F_D) to swim at a constant speed. If accelerating, a virtual mass force (F_{VM}) must be overcome as well. The virtual mass force is the "F = m x a" force required if the fish accelerates with respect to the surrounding water. From Behlke et al. (1991).

SUMMARY OF DESIGN SUGGESTIONS

Behlke et al. (1991), Baker and Votapka (1990), Watts (1974) and Metsker (1970) all describe several different structures, design techniques and construction tips that are used to provide fish passage through culverts. They recommend using one or any combination of the following, recognizing that each culvert site is unique and should be treated as such:

- Incorporate fish passage design features that allow passage of the weakest fish to require passage, in order to maintain the integrity of the aquatic community.
- Make sure that there is no substantial change in channel slope at the culvert site.
- If possible, locate the culvert on a straight part of the stream.
- Make every practical attempt to minimize culvert length.
- Set the culvert at stream grade or slightly flatter; fish can negotiate the resulting steeper natural channel more easily than a steep culvert. Be aware of the increased risk of upstream headcut migration if the culvert is countersunk and no hard point for grade control is used.
- Set the culvert well below stream grade and fill the invert with streambed material; this provides a pseudo-natural streambed within the culvert that makes fish passage easier.
- Select corrugated culverts whenever possible due to hydraulic characteristics that favor fish passage.
- If a smooth walled culvert must be used, attempt to physically roughen the walls or set the culvert below the stream grade.
- Perform a cost analysis to determine if a culvert that provides fish passage is cheaper than the ultimate fish passage structure, a bridge.
- Multiple culverts could be used; one to pass the peak flows and one to pass fish.
- Try to keep flow velocities within the culvert similar to the predicted velocities in the natural channel at the fish passage design flows.
- The best flow for fish passage is free surface, subcritical, outlet (pipe) control flow. Culverts functioning with inlet control at fish passage discharges are not conducive to passage of fish.

- Resting pools could be provided at the inlet and outlet of the culvert to allow fish to rest before and after attempting to pass the culvert. The resting pools should be approximately 2 feet deep (below streambed).

- Consider designing resting areas within a long culvert.

- Avoid having the culvert outlet "perched" above the streambed.

- Avoid the use of concrete aprons on culverts as they tend to provide flow too shallow and fast for easy fish passage.

- Tailwater depth could be increased to cause deeper, slower flow within the culvert and/or to take care of a "perched" outlet. This can be done with one or a series of low head (one foot high) steps or drops constructed of gabion baskets, large rocks, or logs. Large rocks look and work the best when available.

- Flow within culverts is considered deep enough if it is as deep as the design fish's height. If that information is unavailable, six inches (150 mm) should be the minimum flow depth.

- As a last resort, baffles could be installed within a culvert. They are not recommended for new culverts; baffles are discussed in greater detail below.

<u>BAFFLES</u>

The subject of baffles deserves special attention. Baffles, probably the most well known culvert modification used to accommodate fish passage, are vertical obstructions placed across the bottom of a culvert to deflect and check the flow of water. Figure 13 is a sketch of a typical baffle configuration. Baffles are usually made of metal, wood, concrete, or rock and they reduce velocities in steep or undersized culverts to allow fish passage. They also provide intermittent resting areas for fish as they migrate through a culvert. Baffles can provide for deeper flow within the culvert where flow depths are at or below the minimum acceptable levels. Baffles usually have a notch that allows very low flows to pass through the baffle with depth sufficient for fish passage. For a detailed analysis and description of baffle design, Chapter 15 of AASHTO's Model Drainage Manual (1991) should be consulted. Whenever baffles are used, it is important to provide a sinuous low-flow path through the culvert. This would prevent the undesirable development of long, uninterrupted runs of fast water within a culvert.

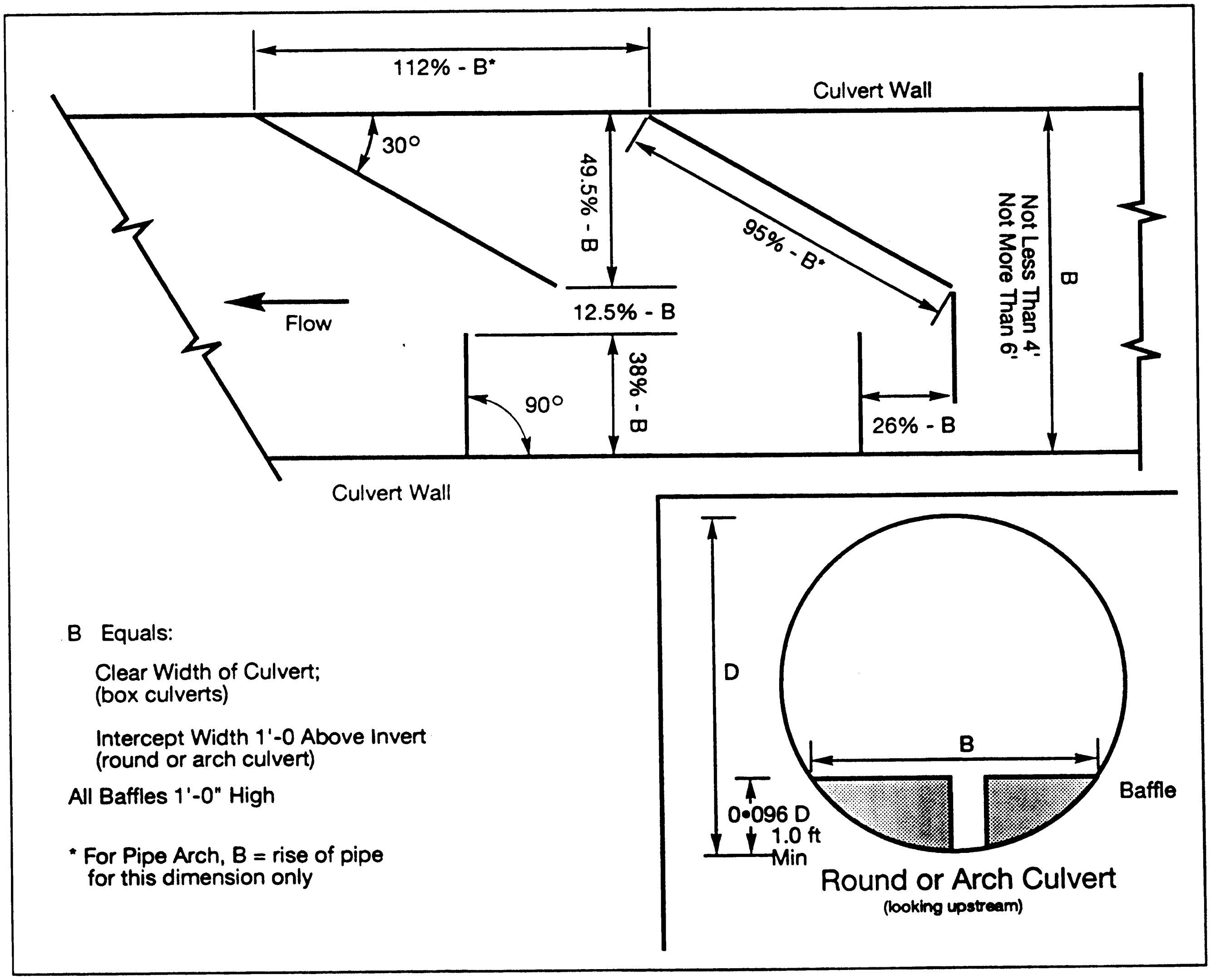


Figure 13: Culvert Baffles. While baffles may have a complex configuration as shown above, most extend straight across the bottom of a culvert with a notch alternating from side to side in order to prevent development of long straight runs of high velocity. From Baker and Votapka (1990).

Baffles can present problems for the engineer and maintenance personnel. They are expensive to install and require periodic maintenance. They are often damaged or blocked by debris, ice, or sediment. Baffles can also reduce the efficiency of a culvert by as much as 30%-40% (Baker and Votapka, 1990), causing an increase in headwater depth for a given flood.

Baffles are useful as a last-resort when retrofitting existing structures to pass fish. The cost of baffles, including maintenance and reduced hydraulic capacity, which reduces design life, must be compared to other alternatives. Different fish passage features can be incorporated into a culvert design before resorting to the use of baffles, including the use of exit sills and pools, countersinking the culvert and selecting a culvert so that the size and shape allow favorable hydraulic conditions for fish passage.

SILLS

Sills are essentially weirs across a channel or culvert that back water up to acceptable depths through the culvert. They are usually located downstream of a culvert, and at low flows they increase flow depth and decrease velocity through a culvert. They are typically V-shaped or notched to allow very low flows to pass the sill at a proper depth.

Sills can be made of gabions, rock, or any other durable material. Gabions are wire baskets filled with rocks; they are versatile, but if placed in a stream, the wires may corrode and fail or bedload may break the wire baskets. A sill constructed of large rock is more durable than a gabion sill and less expensive if a source of large rock is near the culvert site.

Sills are generally inexpensive to install and, in specific cases, may fix a variety of fish passage problems such as inadequate low discharge flow depth, high velocities and outlet perching. Their effectiveness increases as the length and grade of the culvert decreases. They may also provide a pool at the outlet for resting and jumping prior to a fish entering a culvert. If the culvert has a perched outlet, it may be necessary to use more than one sill to "step" the flow up to the exit of the culvert.

POOLS

Fish may need to rest in low-velocity areas before and after expending energy in a culvert. If a culvert outlet is perched, fish need to jump in order to enter the culvert. Properly constructed and maintained resting or jumping pools can be an important culvert design feature.

Pools can be created by excavation below the streambed or by placement of sills. Open bottom culverts generally do not require pools at the inlet and outlet because of the "natural" streambed material through the culvert. However, flow characteristics of other culvert shapes may require that pools be provided at the outlet and/or inlet of the culvert.

Baker and Votapka (1990) recommend an outlet pool depth of at least 0.6 meters (2 feet) as measured from the stream flowline. They also recommend that the width and length of the outlet pool should be twice the culvert span. These dimensions generally allow adequate energy dissipation during high flows as well as furnishing a resting and jumping pool for fish (Baker and Votapka, 1990). Inlet pools do not need to be as large or deep as outlet pools, but they should still furnish areas of low velocity for fish to rest within after passage through the culvert.

MONTANA SPECIFIC STUDIES

There have been previous studies of fish passage through culverts in Montana. These include "Abilities of Trout to Swim Through Highway Culverts" (Belford, 1986) which is summarized and expanded in Belford and Gould (1989). A study by Domrose (1989) analyzed fish passage through a culvert in Ashley Creek near Kalispell. Clancy and Reichmuth (1990) analyzed the success of a detachable baffle system for a culvert that was also in Belford and Gould's 1986 database. These studies are discussed in greater detail below.

BELFORD, 1986

Seven culverts in five different Montana streams were studied from 1984 to 1986 to determine conditions that allowed or prohibited the passage of four species of trout. This study was a combination of field investigations and laboratory swimming stamina tests. All but one of the seven culverts were round corrugated metal pipes (CMP) with the remaining culvert being a corrugated metal pipe arch. Culvert slopes ranged from 0.2% to 4.4% and culvert lengths ranged from 38.0 meters (125 ft) to 94.0 meters (308 ft). Round culvert diameters ranged from 1.6 meters (5 ft) to 5.3 meters (17 ft), while the arch culvert had a span of 6.1 meters (20 ft).

Three different types of culvert modifications were studied: a ladder type removable fishway that collected large bedload in a round culvert; steel baffles fitted within a round culvert; and

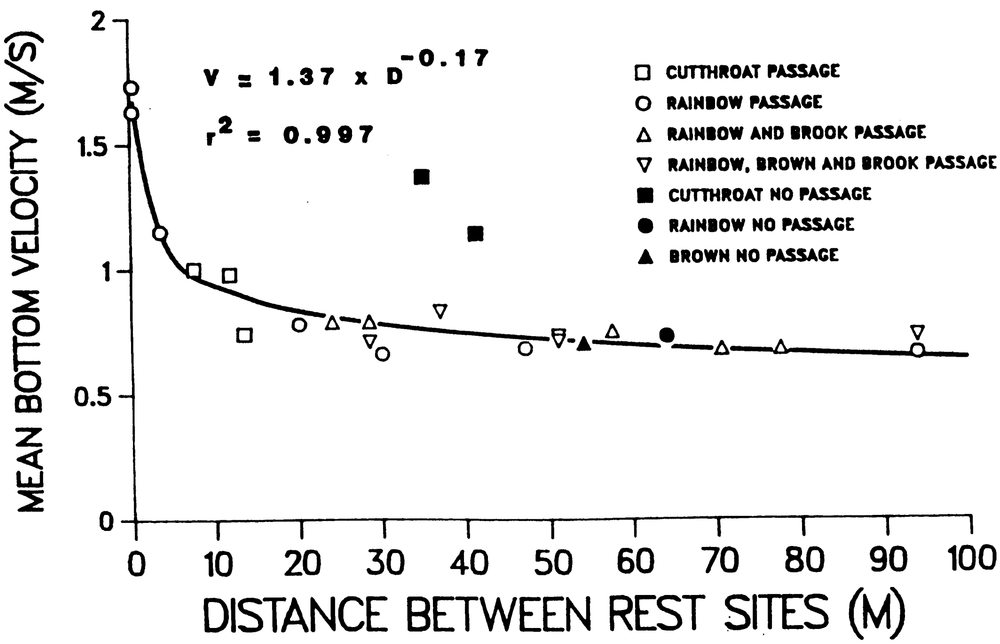


Figure 14: The measurements of mean bottom velocity measured 5 cm above the culvert floor (V) and the distance between resting sites in culverts (D). Points falling above the curve represent conditions that did not allow fish passage, and points falling below the curve represented conditions that permitted passage of fish. From Belford (1986).

countersinking the large arch culvert 0.9 meters (3 ft) below the natural level of the stream, with rock placed in the bottom in an attempt to simulate natural streambed conditions.

Species studied included brook trout, brown trout, cutthroat trout and rainbow trout. Laboratory and field investigations showed similar swimming abilities and stamina for the four species.

A single "threshold" curve (Figure 14) was developed for all four species which relates mean bottom velocity, as measured in the culvert, and the distance between rest sites. Points which plot above the curve represent conditions of no passage and points which plot below the curve represent successful passage. The mean bottom velocity is the velocity expected near the culvert wall, in the zone where fish swim. Using a current meter, the mean bottom velocity was measured 5 cm (2 inches) above the bottom of the culvert and average velocity was measured at 0.6 of the water depth. Velocity was measured at several cross sections throughout the culverts since velocities near the inlets and outlets may be substantially different from those prevailing throughout the culvert. The distance between rest sites was the flow length between large rocks or baffles that provided pools of slow-moving water large enough for fish to rest within. Belford suggested a maximum distance between resting areas of 15 meters (49 ft), but unfavorable culvert slopes and flow depths may result in flow velocities too high for the maximum spacing.

A laboratory swimming speed study was conducted in a circular stock tank modified with two centrifugal pumps to simulate stream velocities ranging from 0.22 meters/second (0.7 ft/sec) to 0.71 meters/second (2.3 ft/sec). Trout taken from the study streams were placed in the tank and electrically stimulated to swim continuously for a specified time at successively higher velocities until they were exhausted and could no longer be stimulated to swim. Data obtained compared favorably to field observations at the culvert study sites and are included in Figure 14.

No significant differences in swimming ability were found between similar-sized specimens of the four trout species. Interestingly, no relationship between passage ability and fish length was observed when sufficient water depth was present. An unverified explanation is that smaller (younger) trout are better able to take advantage of the areas of low velocity that exist near a corrugated culvert wall. It was pointed out, however, that numerous previous studies had shown increases in absolute swimming ability as fish length increased. Behlke et al. (1991) suggested that small fish must overcome smaller drag and gravity forces than larger fish when swimming upstream. This coupled with the ability to better take advantage of lower velocity zones in the flow profile could be another reason for Belford's observation.

Belford recommends that the minimum flow depth be equal to the body depth of the fish. In his study, cutthroat trout moved 11.8 and 13.5 meters (39 and 44 ft) under velocities of 0.98 and 0.74 m/sec (3.2 and 2.4 ft/sec), respectively, when the depth of flow was only 8 cm (3 inches). When irrigation withdrawals reduced flow depths in the same culvert to 4 cm (1.5 inches), the velocities were similar, but trout did not pass.

Darkness within the culverts during daylight hours was found to have no effect on trout passage in this study.

Belford found that the random placement of large individual rocks in a culvert provided good resting sites and would be an inexpensive solution for fish passage problems in many culvert installations. When used, however, the rock should be anchored to prevent its movement during high flows. In his study, a culvert with steel baffles had only five of the original ten baffles intact. A large boulder had tumbled into the culvert and flattened several of the baffles, rendering them ineffective. It was noted that the boulder itself was acting as a large roughness element that provided a resting area in place of some of the damaged baffles.

In summary, Belford found that four species of trout in Montana could negotiate short reaches of relatively high velocity and longer reaches of lower velocity. By shortening the distance between resting sites, ensuring adequate flow depth, and reducing the mean bottom flow velocity, brook, brown, cutthroat and rainbow trout all passed upstream through the study culverts.

BELFORD AND GOULD, 1989

This paper expanded the work originally developed and presented in Belford's (1986) thesis. The original data was used to develop separate mean bottom velocity versus distance between resting area curves for brook, brown, cutthroat and rainbow trout. These curves are similar in shape and magnitude to the single trout curve developed by Belford. Copies of these curves are not included in this report.

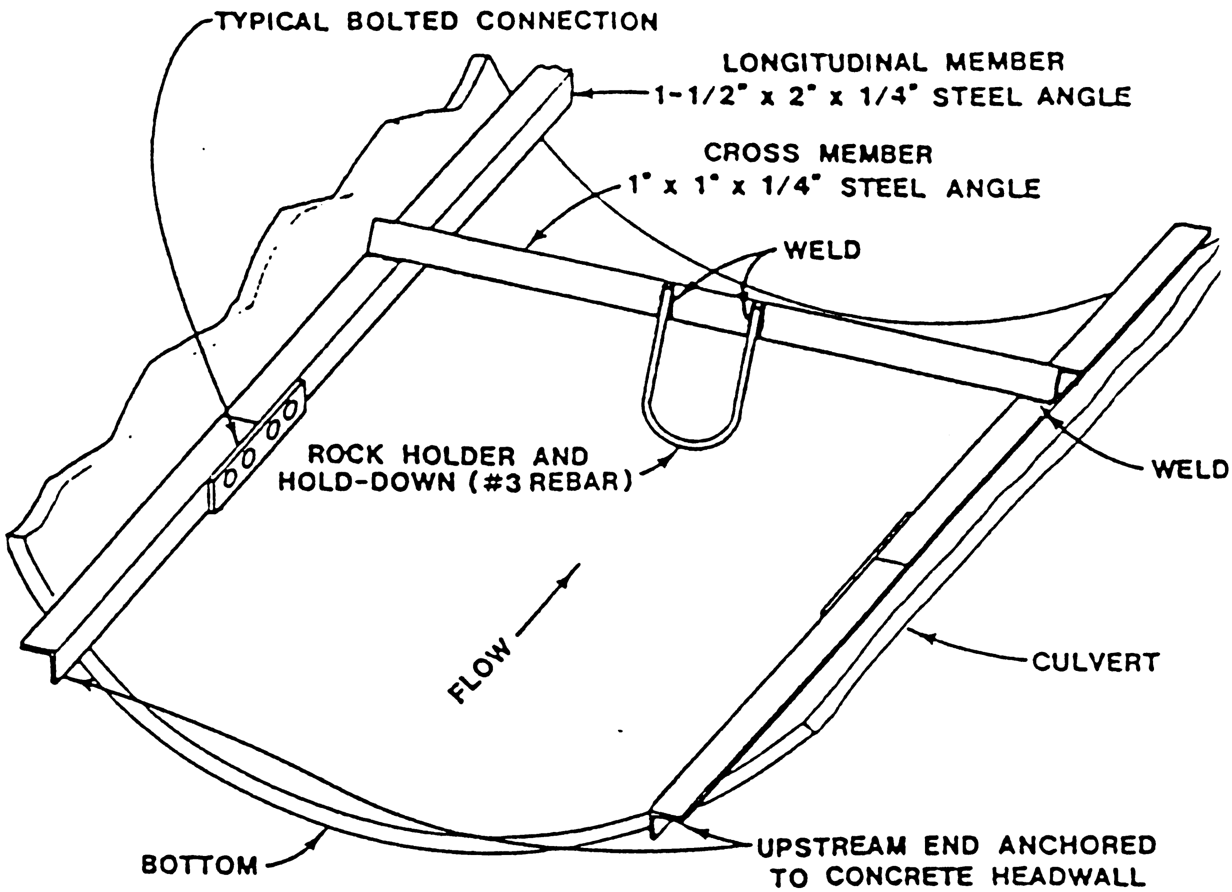


Figure 15: Detail sketch of a removable ladder type fishway. From Clancy and Reichmuth (1990).

CLANCY AND REICHMUTH, 1990

Clancy and Reichmuth (1990) studied the performance of a removable fishway in a culvert on Cedar Creek, a tributary of the Yellowstone River. This site was one of those included in Belford's 1986 study. Clancy and Reichmuth describe in more detail the design and construction of the removable, ladder type fishway placed in one of two culverts set side by side. The other culvert was left unmodified. The culverts are each 45 meters (148 ft) long, approximately 1.8 meters (6 ft) in diameter and each has a slope of 4.4%.

The Montana Department of Highways agreed to the placement of a fish passage structure into only one of the two culverts with the understanding that the structure be easily removable, would not collect debris and no holes could be drilled into the culvert itself. The resulting structure was made out of angle iron and reinforcing bar, and assembled off-site in eight 6.1 meter (20 ft) long sections (Figure 15). Cross-members were placed every 1.2 meters (4 ft). During installation, large rocks were placed just upstream of each cross-member. Complete installation took two men only four hours using hand tools. Total cost for design, labor, materials and installation was $2200. Mean velocity in the culvert was reduced from 2.2 ft/s before installation to 0.7 ft/s after installation. Two months after installation cutthroat trout were spawning upstream of the two culverts in Cedar Creek that had previously blocked the annual spawning migration. Prior to installation, cutthroat trout only spawned in the section of the creek downstream of the unmodified twin culverts. The article was written eight years after the structure was installed, and during that time the fishway appeared to be working very well with no maintenance problems. The fishway passed fish well, but reduced the maximum capacity of the modified culvert by approximately 15%. The low cost and simplicity of this structure demonstrated that retrofitting a culvert for fish passage need not be expensive or elaborate.

DOMROSE, 1989

In 1986, The Montana Department of Transportation (MDT), then known as the Montana Department of Highways (MDOH), proposed replacing a bridge over Ashley Creek with a 120 foot long culvert. The culvert was estimated to be $200,000 to $300,000 less costly than a new bridge. It was eventually decided after lengthy negotiations between MDOH and the Montana Department of Fish, Wildlife and Parks (MDFWP) that a culvert properly designed to allow fish passage would be acceptable.

The 3 meter (10 ft) diameter culvert was 36.6 meters (120 ft) long, with the invert set 0.6 meters (2 ft) below the streambed on a 1% slope. Seven 0.9 meter high steel baffles were installed at 4.6 meter (15 ft) intervals, with the top 0.3 meters (1 ft) of each baffle extending above the normal stream flowline. Each baffle had a 0.6 meter (2 ft) wide trapezoidal notch, with the notches alternating from side to side on adjacent baffles.

Fish passage was monitored during the spring and fall of 1988. The drought of 1988 had little effect on flows through the creek since MDFWP regulates the flows in Ashley Creek from Ashley Lake. Flows ranged from 0.19 to 0.31 m^3/sec (6.65 to 11.0 cfs) during the spring and fall study periods. Average flow velocities measured through each baffle's notch opening ranged from 0.4 to 0.7 m/sec (1.4 to 2.2 ft/sec).

The rainbow and brook trout present in the system had no problem negotiating the measured fish passage flows in this culvert. A recommended maintenance schedule was developed to remove debris from the baffles and keep beaver dams cleared from the culvert to maintain culvert capacity and ensure proper function of the fish passage measures.

CONCLUSIONS AND RECOMMENDATIONS

It must be realized that every site where fish passage is required is unique and deserves special attention; what works very well in one place for one species may not function at all under slightly different conditions. It is the responsibility of the design engineer, the hydrologist and the fishery biologist to make sure that fish are able to pass the culvert in question.

The species, size and swimming ability of the fish that must be passed are critical biological variables. In general, salmonids are stronger swimmers than non-salmonids. Larger fish are stronger swimmers than smaller fish in an absolute sense, but smaller fish are better able to take advantage of the zones of lower velocity found near corrugated culvert walls (Figure 8).
Figures 3, 4 and 5 show relative swimming speeds of adult fish, and Figures 6 and 7 are graphs showing relative swimming performance of adult and sub-adult fish.

Critical hydrologic variables include matching the yearly or daily timing of fish movements with the appropriate streamflows. Fish passage discharges are usually some function of a mean daily or mean monthly flow. Culverts placed in streams are usually designed to safely convey large floods. Design flood frequency for highway drainage facilities is usually determined by an economic analysis, including: constructability, future maintenance concerns, and potential impacts to adjacent land owners and the environment. In general, a larger drainage structure will be able to pass larger flows without damage, but has higher initial costs than a smaller structure. The upstream movements of some species may be delayed at culverts while waiting for peak flows to pass. Figure 9 is a sample hydrograph that allows definition of the peak design flow for arctic grayling in Alaska.

Critical hydraulic variables include average flow velocity near the bottom and sides of a culvert, flow depth and culvert slope. Culvert size, and therefore cost, can be minimized by increasing the hydraulic efficiency through use of a culvert with smooth interior walls and encouraging the culvert to flow full with high flow velocities. Unfortunately, these characteristics are almost always the antithesis to maximizing fish passage efficiency. Shortening the distance between resting sites, ensuring adequate flow depth and reducing the mean bottom flow velocity at fish passage flows allows upstream movement of fish.

There have been previous site-specific studies of fish passage through culverts in Montana. These include "Abilities of Trout to Swim Through Highway Culverts", Belford (1986) which is summarized and expanded in Belford and Gould (1989). Those studies related mean bottom velocity within culverts and distance between resting pools. A study by Domrose (1989) analyzed fish passage through a new culvert that replaced an aging bridge. The culvert was designed with baffles and set below stream grade to provide fish passage. Clancy and Reichmuth (1990) analyzed the success of a detachable baffle system that collected large bedload as a retrofitting of an existing culvert.

Some recommendations for future research and/or policy changes are listed below. It is neither necessary nor reasonable for MDT or MDFWP to attempt to incorporate all of these suggestions into any future research projects or policy decisions; rather, the list should be reviewed by an inter-agency committee to prioritize and/or eliminate options.

- Modify Alaska's DOTPF fish pass com ter program to accommodate Montana species and analyze arch and box culverts instead of simply round culverts. This would require lab studies to determine muscle mass and drag coefficients of various Montana species, since the original program was developed only for arctic grayling in Alaska.

- Write a fish passage sub routine for MDT's Water Surface Profile com ter programs. These programs determine water surface profiles and could accurately determine flow conditions up and down stream from a culvert as well as at sections throughout a culvert. Known swimming abilities could be in t from Bell, 1973.

- Modify Chapter 15 of the AASHTO Model Drainage Manual so that it applies directly to Montana. This is currently under development by the Montana Department of Transportation's Hydraulics Section (McIntyre, 1995). Perhaps this task would be best handled by a joint task force composed of design engineers and fisheries biologists.

- Determine fish swimming speeds for Montana species using flumes in lab studies.

- Find or develop a model for predicting the configuration of the velocity profile within a culvert. This would be used to define how large the zone of low velocity adjacent to a culvert wall would be.

- Perform economic analysis for each crossing and have the MDT/FWP Fisheries Task Force determine which crossings are most worthy of expensive structures to accommodate fish passage. For example, if only $50,000 was available to address fish passage concerns in one portion of the state, how would it be best spent: $50,000 @ one crossing, $5,000 @ 10 crossings, or $500 @ 100 crossings?

- Perform an economic analysis to determine if extensive future research is cost-effective. It may be economically advantageous to over-design a structure to pass fish if future research is expensive and has only limited application in Montana.

- Make sure realistic fish lengths and required times for passage are transmitted from field biologists to designers. For example, a requirement for passage of two-inch long trout 12 months a year may seem unrealistic to the designer. Similarly, the designer should exercise care in developing the runoff hydrograph for the periods when passage is required and design the structure with the appropriate hydraulic conditions.

- Decide whether fish passage is necessary for marginal po lations of fish that do not occur naturally or are not native to a stream.

- An exhaustive inventory of culverts in Montana's streams should be performed. Such an inventory would ideally cover all streams with known fishery value. It would indicate whether culverts were designed or retrofitted for fish passage, how well they are working for fish passage and it should indicate any maintenance problems. Culvert location should be given by stream, township, range, section and name of roadway or feature crossed. Additional information that could be collected includes installation dates, installation personnel and the presence of any stream gage nearby. Some of this information is already loaded onto the Montana River Information System database, but data should be verified and updated before use.

- The Montana Department of Transportation's design staff could recommend several different sizes and types of culverts and/or bridge openings. Minimum sized culverts that could pass design flows without regard to fish passage requirements would be specified, with larger more expensive structures recommended as design options. If the more expensive structure was needed to pass fish, a decision could be made to select the appropriate alternative.

- Survey the fisheries biologists around Montana to determine which species would be the primary species they deal with in streams where culverts are most likely to be placed. Are these in perennial streams? Are the species only game species?

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