Maine Department of Transportation
Design Guide for Fish Passage Through Culverts

Introduction

This manual is intended for the design of new and replacement culverts, as well as culvert rehabilitations, that will not block passage of identified fish species at specified design flows. Engineers will find these design guidelines useful in the implementation of Maine Department of Transportation (Maine DOT) fish passage policy as documented in the companion volume to this work (Maine DOT, 2004a). The manual is intended for use by Maine DOT engineers and designers as well as other engineers designing stream crossings in a fisheries environment. At this stage in the development of fish passage methodologies in Maine, stream crossings design for fish passage should be performed by or under the direct supervision of an experienced hydraulic engineer working with a fisheries biologist.

This manual is limited to culverts and does not address dedicated fishway passage structures. Furthermore, while it is recognized that culverts are usually the most desirable road crossing for small and medium sized streams from an engineering standpoint, from a fish passage perspective culverts are in fact less desirable than bridges and bottomless arches on footings.

Culvert Barriers to Fish Passage

There are several common conditions at culverts that can create barriers to fish movement:

- excess drop at culvert outlet
- high velocity within culvert barrel
- inadequate depth within culvert barrel
- turbulence within culvert barrel
- debris accumulation at culvert inlet

Barriers are created by several conditions. Culverts are usually uniform and sized to pass peak design flows, e.g., the 50-year flood Q_{50}. They do not have the roughness and variability of natural stream channels and therefore do not dissipate kinetic energy effectively. Thus, velocities tend to be higher in a culvert than in the stream. This effect is amplified by the fact that existing culverts are often narrow, with a concomitant constriction of flow at the inlet. This may have the effect of increasing velocity in the pipe, creating turbulence at the inlet, and creating velocity-induced scour holes at the outlet. Outlet scour may induce a significant drop at the outlet. The last barrier condition, debris accumulation, is due to inadequate maintenance.

New and replacement stream crossings can be designed to avoid the first four, hydraulics related, barrier conditions. The last condition, even in a well-designed culvert, depends on good maintenance attuned to the specific fish passage requirements of a culvert. Fish passage can be difficult to restore in rehabilitated and retrofit culverts. Mitigating design elements in addition to the basic culvert lining are usually needed in order to establish passage under specified conditions.

Design Objectives

In designing for fish passage through culverts, two objectives are paramount:

- maintain depth equal to or greater than the necessary minimum
- keep velocity less than or equal to limiting maximum sustainable fish swimming speed

Strictly speaking, these limiting values are determined by the target species of interest, the time of year they are moving, and the direction they are moving in. This information is summarized in Appendix 1B of the Fish These factors, combined with watershed hydrology and channel geomorphology, provide the information necessary for estimating an appropriate passage design flow.

While species-specific design is never inappropriate, the design process can be simplified by employing generic design parameters that produce robust designs suitable for most species of interest in Maine. Therefore, Maine DOT recommends the following generic design objectives:

- maintain at least 8 inch water depth
- limit flow velocity to no more than 2 ft/s
- limit drop in water surface elevation at outlet to 2 inches
- use average of median September and October flows as design flow

If a feasible design cannot be produced for these generic standards, then the design should be refined according to species-specific requirements in Appendix 1B.

General Steps in Design for Culvert Fish Passage

The following steps are generally followed when addressing fish passage through culverts.

1) identification of valuable habitat for specific species and need for passage by fisheries biologists in MDOT, resource agencies, and regulatory agencies
2) determination of calendar periods when passage must be provided
3) estimation of design flows during passage periods
4) culvert design
    a) new pipe: size pipe according to natural stream bankfull cross-section; check for extreme flow capacity and passage performance by hydraulic analysis
    b) rehabilitated pipe: hydraulic analysis to check performance of proposed rehabilitation; design mitigation measures (e.g., weirs, baffles, outlet notch ramps) if fish passage is inadequate

Fish Habitat Considerations In and Adjacent to Culverts

There are several aspects of fish habitat that warrant consideration in passing fish through culverts. Inside the culvert, the issue is the culvert bottom. For traditional enclosed circular culverts and multi-plate pipe arches, a natural bottom can be simulated with varying degrees of success by embedding the pipe. Detailed recommendations are given later in this report. Open bottom provide a natural, and therefore superior, bottom habitat. However, such structures can cost significantly more than enclosed culverts.

Culvert inlets and outlets are often treated with riprap to protect the structure and prevent erosion and scour. Riprap should not be overused in sensitive fisheries, for esthetic reasons and to minimize the heat sink effect of large rock masses that could warm the stream.

Stream bank vegetation in the vicinity of inlets and outlets should also receive attention. Energy dissipation pools and scour pools are usually features of culvert outlets. Adequate natural shading will increase their attractiveness to fish.

Design Approaches: New & Rehabilitated Culverts

Two basic design approaches are employed by MDOT. For new and replacement culverts, the preferred approach is to match culvert dimensions and gradient to natural bankfull stream channel hydraulic geometry, subject to standard MDOT culvert design practices. The assumption is that by eliminating perched outlets and matching hydraulic geometry in the range of critical fish passage flows, fish passage is assured. The validity of this assumption should be checked in each design. This approach simplifies design and construction and minimizes the hydraulic and hydrologic analysis necessary.

For culvert rehabilitation (e.g., by slip or invert lining), additional hydraulic analysis and design is necessary. In this case, hydraulic analysis is employed to estimate water velocities and depths under design flows. Analysis is also employed to design mitigation measures (e.g., weirs) needed to achieve velocities and depths that will pass fish. While the hydraulic approach is not required for designing new and replacement culverts, the hydraulic performance of such pipes should be checked for standard design floods (e.g., Q_{50}) as well as fish passage flows.

For both new and rehabilitated pipes, grade control structures (i.e. weirs) can be used to provide both adequate water depths and velocities. When weirs are utilized, the level of hydraulic analysis is simplified. It is anticipated that various weir configurations will see increased use when fish passage must be provided.

Hydraulic Considerations in Culvert Fish Passage

New and replacement culverts must be designed to pass the 50-year flow event (or “flood”) in accordance with Maine DOT Drainage Policy. Rehabilitated culverts should be evaluated for their ability to pass the 50-year flood, though the reduction in cross-sectional area and effects of fish passage mitigation measures may reduce the pipe capacity. Extreme flows should be estimated according to the methods used by Maine DOT in highway and bridge design.

In addition to the traditional peak flow design standard, culverts in selected fisheries should permit fish passage during a range of low flows. Two potential hydraulic problems are addressed in designing for fish passage. Water depth in the culvert may be inadequate to permit movement. Also, the velocity in the culvert may be too high for fish to swim against in an upstream direction.

These potential barriers to passage establish two design objectives. These criteria are species-dependent and are summarized in the Maine DOT Fish Passage Policy. Occasionally, resource and regulatory agencies may directly specify a minimum depth and/or maximum velocity to be achieved. The two design objectives relate to depth and velocity:

1) maintain adequate in-culvert water depth for identified species during low flow conditions to allow passage;
2) during periods of upstream movement, flow velocity should not exceed species swimming capacity while adequate depth is maintained

These design standards are species- and season-dependent. The depth and flow velocity should be determined by hydraulic analysis and checked against species-dependent criteria. When a weir-and-pool configuration is employed, In the case of proposed rehabilitation, failure to meet standards will require mitigation measures or possibly a replacement pipe.

Culvert Outlet Hydraulics: Energy Dissipation Pools

Compared to a natural stream reach of the same length, a culvert tends to dissipate less energy and therefore water exits a culvert with more kinetic energy than the stream reach. Unless properly addressed, this elevated energy will tend dissipate by excavating a scour pool. This pool may develop to such an extent that the culvert becomes perched and blocks fish passage. The elevated exit velocities may also exceed the swimming capacity of fish. These undesirable effects can be mitigated by constructing energy dissipation pools at culvert outlets. The pools also provide areas where fish can rest prior to their entry into culverts.

The following guidelines should be followed in pool design:

- pool hydraulics should be designed using the fish passage design flow
- the pool outlet is maintained by a push bar or weir at the appropriate elevation and flow capacity. The design water elevation should enable fish entry into the culvert. Weir design is discussed later in this report.
- The pool should be stabilized to prevent scour and erosion. The pool outlet structure elevations should be secure so as to maintain desired hydraulic performance.
- Use of riprap should be minimized and concentrated on protecting the culvert outlet and pond outlet structure. The banks may also be protected at the

discretion of design and environmental staff. Riprap should not be placed in the pool bottom.

- Pool width should be at least 2 times the culvert span.
- Pool length should be at least 3 times the culvert span.
- For single barrel installations only, the culvert and pool centerlines should align.
- The pool should be at least 3.25 ft (1 m) deep at the design passage flow.
- A minimum of three boulders should be placed in a triangular pattern in order to create fish resting areas. The boulders should be approximately 3.25 ft (1 m) in diameter (2.5 ft (0.75 m) diameter for culvert D $\leq$ 5 ft)
- The pool outlet structure (push bar, weir or channel) should be designed for hydraulic consistency with in-culvert weirs. See extended design discussion later in this report.
- If outlet is riprapped, voids should be filled with smaller rock to prevent underflow and throughflow.

Culvert Alignment

Ideally culverts are aligned with the stream and take the shortest path possible beneath the road. In all cases, design should make every effort to minimize impact on the stream. If stream alignment results in a skewed pipe longer than 100 ft (30 m), then the pipe should be placed at right angles to the road in order to minimize the pipe length. In such cases, special consideration should be given to potential bank erosion at the culvert entry and exit.

Hydrology and Design Flows for Fish Passage

The passage design flow depends on the time of year for passage, which in turn depends on the species of interest. In general, fish are moving from April through June and September through October; the low-flow months of high summer are periods of lower activity. Critical movement does not take place during the warm-water months of July and August. Design flows will have to be assigned on a case-by-case basis, since they are dependent on both watershed and passage period (which depends on species of interest; see Appendix 1B in the Fish Passage Policy.

The design flows may be determined by several different methods:

1) site inspection, channel geometry measurements, and flow measurement during periods of fish movement
2) hydraulic calculation from channel geometry measurements and specified or known flow depths for fish passage
3) estimation by USGS regression equations for monthly median flows (Dudley, 2004; Appendix 2A)

When using the equations for median monthly flows, the estimates for September and October are significantly lower than for April though June. Therefore, using the average of the September and October medians should produce a conservative design that also maintains needed depths during the late spring, higher flow months. The median flow regression equations are tabulated in Appendix 2A; easy-to-use look-up charts are also given for May, June, September, October, and the September-October average.

Method (1) is the single best method but it may not always be possible to collect data during fish passage periods. Except for winter months, data for method (2) can always be collected and therefore hydraulic estimation should be performed in most cases. Method (3), regression calculation, should always be carried out because it does not require any field work and only requires data from paper maps or available as GIS coverages from the Maine State GIS Internet web site.

Strictly speaking, the target flow for fish passage design should be species-dependent. Ultimately, the species type, age, direction of movement, and month(s) of movement should all indicate the flow or multiple flow values that will govern the design for fish passage. This information is summarized in Appendix 1B of the Fish Passage Policy. As a practical matter, this approach greatly complicates a design process which invariably occurs within a context of sharply limited alternatives. Maine DOT therefore recommends that in the absence of site-specific data, it is sufficient to execute design on the basis of the average of the September and October median monthly flows. This value is close to the lowest average baseflow value of the year; if adequate depth is obtained this with flow then higher depths will be obtained for the remainder of the year.

New and Replacement Culverts: Hydraulic Geometry Matching

Designing new and replacement culverts for fish passage is generally simpler than retrofitting existing pipes. The following guidelines should be followed:

1) Employ corrugated elliptical pipe arches with the largest feasible corrugations whenever possible
2) Embed pipe: for nominal diameter (or rise) $D < 48$ in (1200 mm), embed pipe invert 6 in (150 mm) in stream bed; $D \geq 48$ in (1200 mm), embed pipe invert 12 in (300 mm); allow embedded pipe to fill with natural substrate
3) Match pipe and stream flow geometry: flow depth and width in the pipe at bankfull flow (approximately 1.1-year return period) should approximate depth and width in the stream
4) Place pipe with zero slope, or as nearly flat as possible
5) Size pipe for peak flow: pass the 50-year flood, accounting for the capacity lost to embedding
6) Check fish passage performance: perform hydraulic analysis for depth and velocity during fish passage flows; irregular cross-section flow area (due to embedding and elliptical section) should be accounted for.

The new culvert should not construct flow at the inlet over the range of design flows, as this will increase flow velocity and attendant kinetic energy complications. If a constriction cannot be avoided, then in-culvert weirs for water level control should be investigated.

Figure 1 shows an embedded circular pipe along with equations in Table 1 for calculating basic geometric quantities. Table 2 gives equations for embedded pipe arches; Table 3 gives corresponding tabulated values.

Figure 1: Embedded Circular Pipe

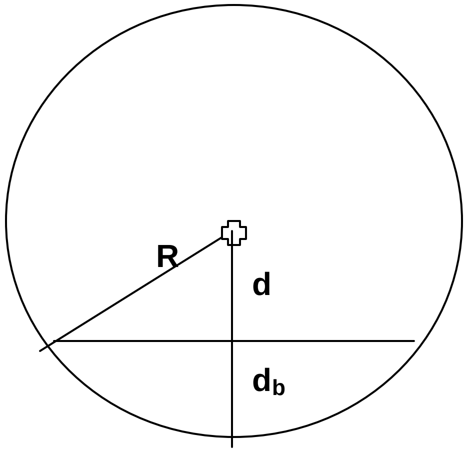


Table 1: Equations for Embedded Circular Pipe Geometry

Radius; diameter; embedded depth	R; $D = 2R$; d_b
Distance from bed to pipe center	$d = R - d_b$
Bottom embedded width	$w_b = 2\{d_b(D-d_b)\}^{1/2}$
Embedded Area	$A_b = R^2\cos^{-1}[(R-d_b)/R] - d w_b/2$
Open Area	$A_o = \pi R^2 - A_b$
Embedded Perimeter	$P_b = D\cos^{-1}[(R-d_b)/R]$
Open Perimeter	$P_o = \pi D - P_b$

These equations can be used to approximate elliptical pipes, with pipe rise substituted for diameter. More exact results for elliptical pipes can be calculated with the following equation:

$$A = b\,(\text{pipe rise})^a$$

The coefficients a and b are given in Table 2. Note that two sets of coefficients are given, for corner radii of 18 in (457 mm) and 31 in (787 mm). These coefficients were developed by regression analysis from the exact tabulated areas in Tables 3a and 3b, respectively. The tables can be used in place of the equations.

Table 2: Function Coefficients for Open Area in Embedded Pipe Arch

Corner Radius		**Depth of Embedment**			
		0 mm	150 mm (6 in)	225 mm (9 in)	300 mm (12 in)
457 mm	a	2.246	2.316	2.371	2.428
	b	0.995	0.893	0.823	0.752
787 mm	a	2.260	2.291	2.320	2.351
	b	0.859	0.807	0.766	0.721
18 in	a	2.246	2.316	2.371	2.428
	b	0.743	0.613	0.530	0.453
31 in	a	2.260	2.291	2.320	2.351
	b	0.631	0.571	0.524	0.475

Equation: open area $A = b \times (\text{pipe rise})^a$, in (m, m^2) and (ft, ft^2)

Table 3a
OPEN AREA IN EMBEDDED PIPE ARCH (metric)

	Span (m)	Rise (m)	Open Area (m^2)			
			Depth of Embedding (mm)			
			0 mm	150 mm	225 mm	300 mm
Corner Radius = 457 mm	1.855	1.397	2.048	1.854	1.733	1.602
	1.931	1.448	2.231	2.061	1.936	1.800
	2.058	1.499	2.433	2.275	2.143	2.002
	2.134	1.550	2.630	2.450	2.313	2.165
	2.210	1.601	2.838	2.638	2.493	2.338
	2.337	1.651	3.062	2.876	2.727	2.565
	2.414	1.702	3.275	3.068	2.911	2.743
	2.490	1.753	3.504	3.272	3.105	2.929
	2.617	1.804	3.743	3.533	3.371	3.185
	2.693	1.855	3.985	3.750	3.573	3.383
	2.846	1.905	4.255	4.041	3.866	3.672
	2.896	1.956	4.503	4.278	4.080	3.878
	2.973	2.007	4.767	4.501	4.303	4.092
	3.125	2.058	5.049	4.817	4.623	4.409
	3.252	2.109	5.343	5.123	4.923	4.740
	3.328	2.160	5.634	5.395	5.196	4.972
	3.481	2.210	5.950	5.727	5.541	5.321
	3.532	2.261	6.235	5.994	5.785	5.561
	3.608	2.312	6.544	6.283	6.064	5.820
	3.760	2.363	6.887	6.643	6.441	6.203
	3.811	2.414	7.194	6.932	6.706	6.461
	3.862	2.464	7.522	7.236	7.026	6.729
	3.913	2.541	7.945	7.628	7.374	7.100
	4.090	2.566	8.221	7.937	7.700	7.426
	4.243	2.617	8.600	8.335	8.115	7.854
	4.294	2.668	8.946	8.662	8.417	8.147
	4.345	2.718	9.302	8.994	7.823	8.444
	4.522	2.769	9.720	9.434	9.197	8.943
	4.675	2.820	10.122	9.855	9.631	9.367
	4.726	2.871	10.497	10.212	9.974	9.693
	4.776	2.922	10.884	10.579	10.325	9.810
	4.827	2.998	11.399	11.071	10.798	10.478
	5.005	3.023	11.729	11.425	11.171	10.872
	5.056	3.074	12.135	11.809	11.538	11.217
Corner Radius = 787 mm	4.040	2.846	9.080	8.833	8.615	8.391
	4.116	2.896	9.461	9.197	8.977	8.728
	4.268	2.947	9.880	9.629	9.420	9.174
	4.319	2.998	10.247	9.981	9.756	9.503
	4.395	3.049	10.646	10.360	10.123	9.854
	4.548	3.100	11.087	10.819	10.595	10.331
	4.675	3.150	11.511	11.254	11.039	10.787
	4.751	3.201	11.934	11.663	11.436	11.170
	4.827	3.252	12.370	12.073	11.826	11.535
	4.954	3.303	12.809	12.534	12.306	12.038
	5.030	3.354	13.255	12.966	12.724	12.442
	5.183	3.404	13.739	13.447	13.205	12.919
	5.234	3.455	14.017	13.724	13.481	13.193
	5.310	3.506	14.645	14.337	14.079	13.777
	5.462	3.557	15.153	14.859	14.615	14.326
	5.513	3.608	15.608	15.300	15.042	14.738
	5.666	3.659	16.131	15.835	15.589	15.298
	5.716	3.709	16.605	16.294	16.036	15.730
	5.869	3.760	17.147	16.847	16.598	16.305
	5.945	3.811	17.662	17.347	17.087	16.779
	5.996	3.862	18.160	17.830	17.559	17.237
	6.072	3.913	18.693	18.348	18.059	17.719
	6.225	3.963	19.257	18.928	18.654	18.331
	6.275	4.014	19.772	19.427	19.139	18.799

Table 3b
OPEN AREA IN EMBEDDED PIPE ARCH (U.S. Customary)

	Span (ft)	Rise (ft)	Open Area (ft^2)			
			Depth of Embedding (in)			
			0 in	6 in	9 in	12 in
Corner Radius = 18 in	6.08	4.58	22.03	19.95	18.64	17.24
	6.33	4.75	24.00	22.17	20.83	19.37
	6.75	4.92	26.17	24.47	23.06	21.54
	7.00	5.08	28.29	26.36	24.88	23.29
	7.25	5.25	30.53	28.38	26.82	25.15
	7.67	5.42	32.94	30.94	29.34	27.60
	7.92	5.58	35.23	33.01	31.32	29.51
	8.17	5.75	37.70	35.20	33.41	31.51
	8.58	5.92	40.27	38.01	36.27	34.27
	8.83	6.08	42.87	40.34	38.44	36.40
	9.33	6.25	45.78	43.48	41.59	39.50
	9.50	6.42	48.44	46.02	43.89	41.72
	9.75	6.58	51.29	48.42	46.29	44.02
	10.25	6.75	54.32	51.82	49.74	47.43
	10.67	6.92	57.48	55.11	52.96	51.00
	10.92	7.08	60.61	58.04	55.90	53.49
	11.42	7.25	64.01	61.61	59.61	57.25
	11.58	7.42	67.08	64.49	62.24	59.83
	11.83	7.58	70.40	67.59	65.24	62.61
	12.33	7.75	74.09	71.47	69.30	66.73
	12.50	7.92	77.40	74.58	72.15	69.51
	12.67	8.08	80.93	77.85	75.59	72.39
	12.83	8.33	85.48	82.07	79.33	76.38
	13.42	8.42	88.44	85.39	82.84	79.89
	13.92	8.58	92.52	89.67	87.30	84.50
	14.08	8.75	96.25	93.19	90.55	87.65
	14.25	8.92	100.07	96.76	84.16	90.84
	14.83	9.08	104.57	101.50	98.95	96.21
	15.33	9.25	108.90	106.02	103.61	100.77

	Span (m)	Rise (m)	Open Area (ft^2)			
			Depth of Embedding (in)			
			0 in	6 in	9 in	12 in
	15.50	9.42	112.93	109.86	107.30	104.28
	15.67	9.58	117.09	113.81	111.08	105.54
	15.83	9.83	122.64	119.11	116.17	112.73
	16.42	9.92	126.19	122.91	120.18	116.96
	16.58	10.08	130.55	127.05	124.13	120.68
Corner Radius = 31 in	13.25	9.33	97.69	95.03	92.68	90.27
	13.50	9.50	101.79	98.94	96.58	93.90
	14.00	9.67	106.29	103.59	101.34	98.70
	14.17	9.83	110.24	107.38	104.96	102.24
	14.42	10.00	114.53	111.46	108.91	106.01
	14.92	10.17	119.28	116.39	113.98	111.14
	15.33	10.33	123.84	121.07	118.76	116.05
	15.58	10.50	128.39	125.47	123.03	120.17
	15.83	10.67	133.08	129.89	127.23	124.10
	16.25	10.83	137.80	134.85	132.39	129.51
	16.50	11.00	142.60	139.49	136.89	133.86
	17.00	11.17	147.81	144.67	142.06	138.99
	17.17	11.33	150.80	147.65	145.03	141.94
	17.42	11.50	157.56	154.24	151.47	148.22
	17.92	11.67	163.02	159.86	157.23	154.12
	18.08	11.83	167.92	164.60	161.83	158.56
	18.58	12.00	173.54	170.36	167.71	164.58
	18.75	12.17	178.64	175.30	172.52	169.23
	19.25	12.33	184.47	181.25	178.57	175.42
	19.50	12.50	190.01	186.63	183.83	180.52
	19.67	12.67	195.37	191.82	188.91	185.44
	19.92	12.83	201.11	197.39	194.29	190.63
	20.42	13.00	207.17	203.64	200.69	197.21
	20.58	13.17	212.72	209.00	205.91	202.25

Steeply Sloped Streams

This approach of matching pipe flow and depth to the natural stream works best with gentle slopes. Steeply sloped streams (slope $S > 3\%$) require extra care and will likely require mitigation (e.g., weirs or baffles). Embedding pipes to below natural stream bed elevation may inadvertently allow headcutting to propagate upstream of the culvert inlet. Therefore, pipes should placed on the natural stream bottom when slope exceeds 3%. Hydraulic analysis may indicate the need for in-pipe grade control in order to maintain adequate water depths. Downstream control may also be needed.

Rehabilitated Culverts - Corrective Measures

Existing culverts can be rehabilitated by slip lining and by invert lining. However, linings reduce both cross-sectional flow area and surface roughness, with a possible net effect of decreasing flow depth and/or increasing flow velocity. The simplest approach to maintaining fish passage is to install a new culvert designed for consistency with the prevailing stream hydraulic geometry. Budgetary and other constraints may argue against replacement. If the culvert is on an identified fishery, then design measures may need to be taken in order to insure fish passage under specified conditions.

When selecting a passage mitigation measure, the first step is to determine if the lined culvert will be a barrier to passage by appropriate hydraulic and hydrologic analysis. Target design flows are chosen according to guidelines presented here and in the companion Maine DOT Fish Passage Policy volume (2004a). Then the lined pipe is evaluated for acceptable depth and velocity, according to the target species. In general, if downstream control on shallow water depths does not previously exist, then measures measures are likely necessary.

When a pipe is lined, the invert is raised by approximately 5 in (125 mm) due to the concrete or plastic lining. This may create a slightly hanging invert or a drop too great for fish to pass over. This effect is separate from the hydraulic aspects of depth and velocity. A sluice channel in the outlet, combined with one or more in-pipe weirs, can be employed to eliminate this drop. Alternatively, downstream external weirs can also be used, though right-of-way complications may eliminate this option.

Culvert hydraulic analysis can be performed with software such as HY8 or equivalent proprietary software for the design flows and incorporating tailwater conditions as determined by site inspection. If flow depth is too shallow or velocity too high, then the following general measures suggest themselves for increasing depth. In order of preference, they are

- tailwater control structures (weirs) installed downstream
- weirs installed in the culvert
- Sluice channels in bottom of culvert (culvert end treatments for fish passage)

When considering corrective measures, the first choice should be simple downstream weirs. Downstream weirs are particularly useful if a perched outlet is the major problem. Depending on the severity of the perch, more than one weir may be needed. As noted, right-of-way limitations may rule out this option. Downstream weirs may also be useful for maintaining adequate water depths in culverts that are not too steep. External weirs offer advantages in construction in maintenance over other available measures.

When the lining-induced drop is not too great, and if downstream weirs are not an option, a simple cutout notched sluice channel in the bottom of the culvert and extending up into the culvert may provide adequate water depth. However, by itself, this cutout channel is usually not adequate. Some potential problems include high velocity within the channel and inadequate depth above the termination of the cutout. In most cases such an outlet will need to be combined with grade control, within the pipe, downstream, or both.

In steeper pipes, in-culvert grade control achieved with simple pool-and-weir sequences should be considered. This approach is limited to larger pipes (D > 5 ft (1500 mm) minimum, and preferably D > 6 ft (1800 mm)). Maine DOT no longer encourages the use of culvert baffles and expects that typical fish passage challenges can be met with the measures outlined here. These measures will now be discussed in more detail.

Culvert End Treatments for Fish Passage – Cutouts or Notched Outlets

A culvert lining raises the outlet invert. If the induced jump is modest, it can be mitigated by building a ramped notch (cutout or sluice channel) into the bottom of the culvert. The ramped notch is like a sluiceway built into the bottom of the pipe. The outlet notch invert is at stream grade, providing a continuous stream/culvert bottom elevation. The channel returns to the prevailing culvert invert elevation some distance into the culvert.

Typical details for two different culvert end treatment options are show in Figures 2 (Option 1; notch terminates at end of pipe) and 3 (Option 2; notch extends beyond pipe). Treatment 1 is intended for modest drops while treatment 2 is for deeper drops. Treatment 1 includes a riprap apron to provide a smooth transition from stream bed to the pipe edge. The notched channel should be sized to run full at low flow.

This treatment is used primarily to eliminate hanging inverts. End treatments by themselves will not correct excessive velocities or inadequate depths farther up the culvert. Hydraulic analysis should be performed to check that:

1) adequate flow depth is achieved in the upper portion of the pipe
2) velocity standard is not exceeded in pipe and notch channel

As a practical matter, it is likely that notched channels will have to be combined with at least one in-culvert weir.

Regardless of the specific end treatment, care should be exercised in the use of rock riprap. Rock absorbs solar and thermal energy and therefore functions as a heat sink. Excessive rock can lead to warming of the stream water, possibly creating a thermal barrier to fish passage.

Figure 2: End Treatment to Eliminate Drop, Option 1

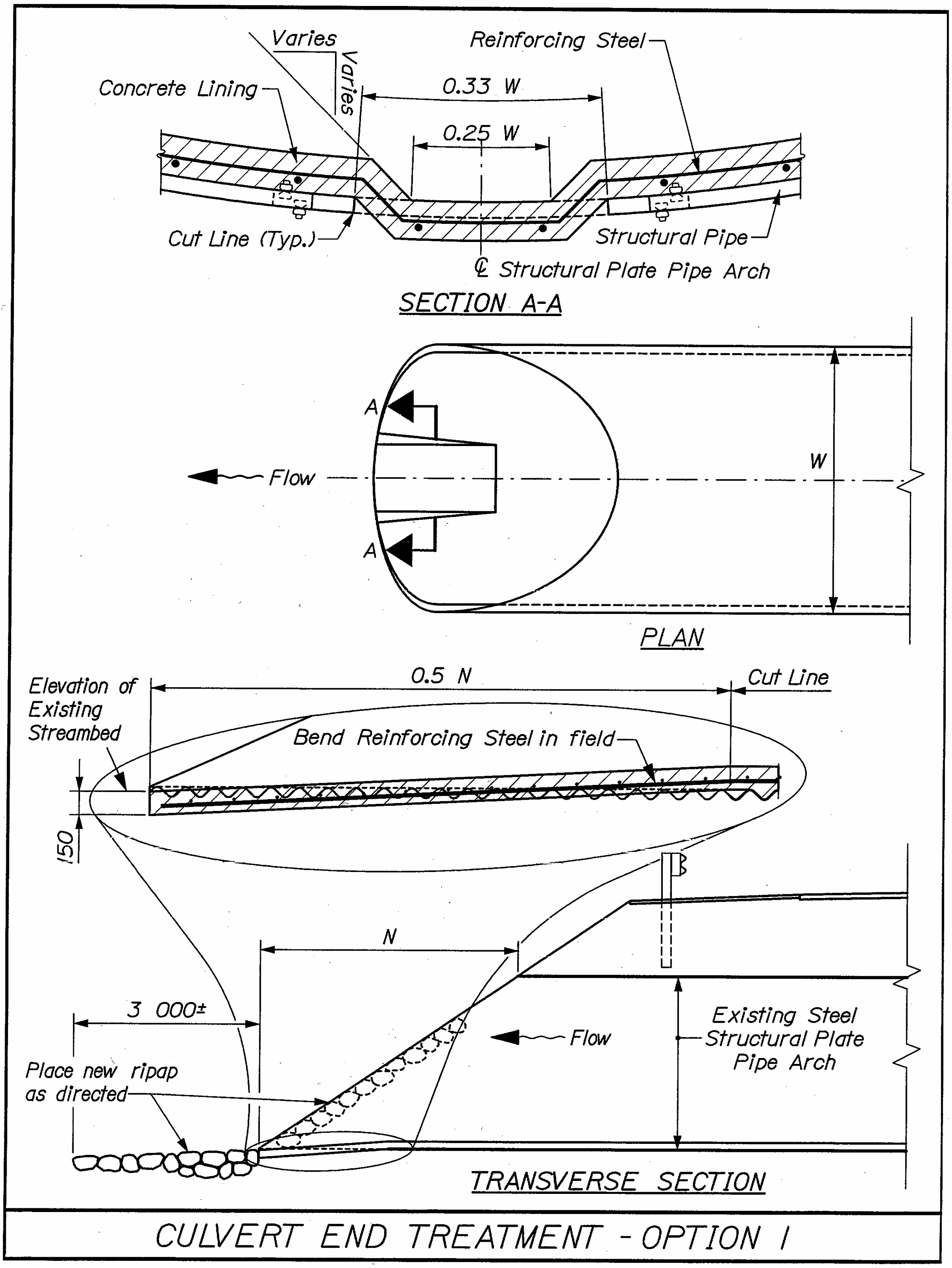
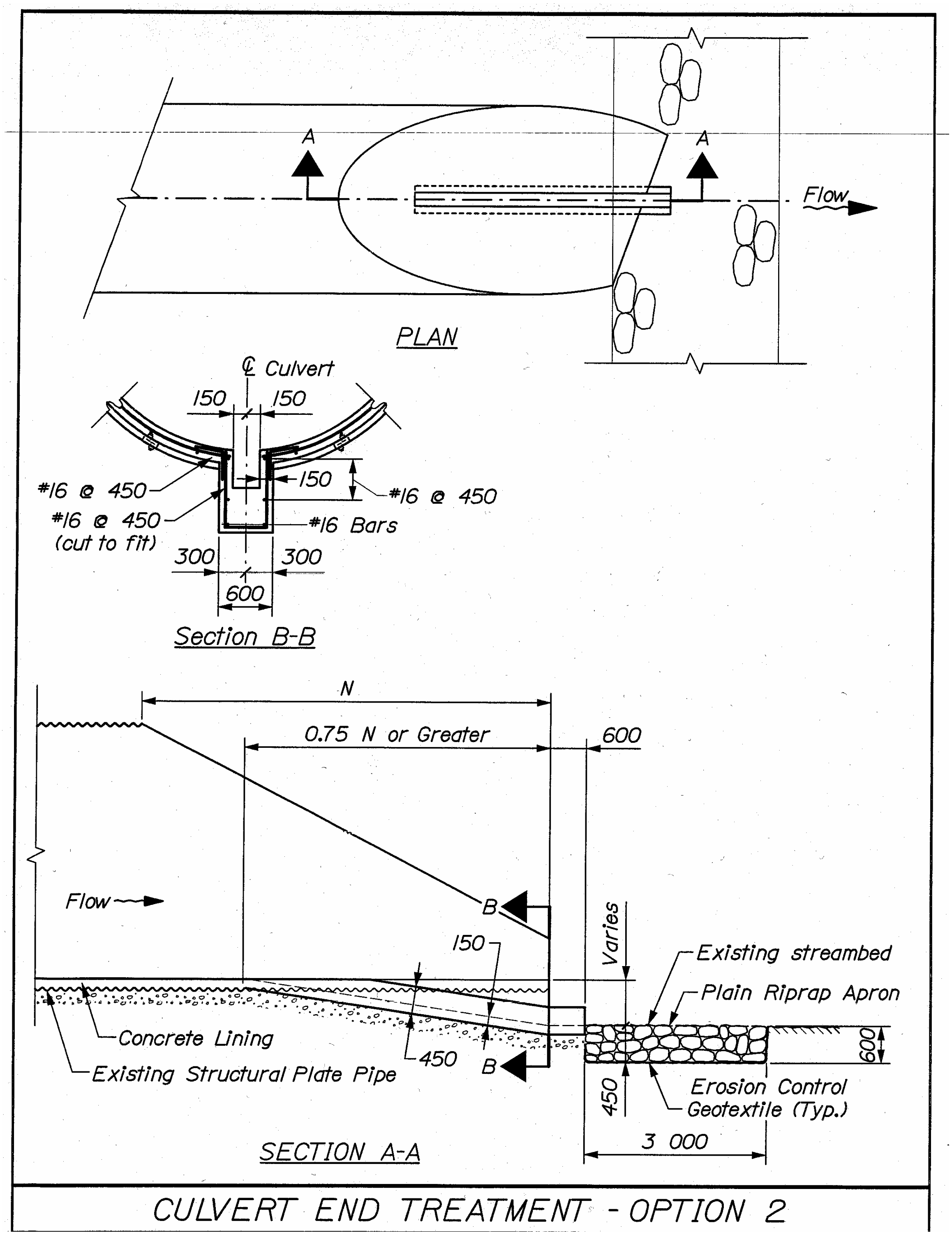


Figure 3: End Treatment to Eliminate Drop, Option 2



Downstream Grade Control Structures (Weirs)

Downstream weirs are used to establish grade control, i.e., to back water up into the culvert to the needed depth. It may be possible to maintain adequate depth and velocity solely with external weirs. In a sloping culvert, the minimum depth would be achieved at the culvert inlet. This depth and location helps to fix the design parameters of the downstream weirs; the design flow completes the determination of the weir parameters. Specific weir dimensions and their calculation are discussed in detail for in-culvert weirs.

Drops in water level are created at weirs and this drop initself may constitute a barrier to passage. The drop at any particular weir should ordinarily be limited to 8 in (200 mm) or a species-specific value in order to allow for passage over the weir, and the weir notch should be submerged 4 in (100 mm) on the downstream side. Thus, several weirs in series may be needed to create the needed tailwater elevation. The distance between weirs should be about 150% of the stream width in smaller streams, with a target minimum spacing of 16.5 ft (5 m), up to 33 ft (33 m) in larger streams. Actual spacing depends on stream slope. For reasons of cost and downstream impact, the number of structures should be kept to a minimum.

A cost-effective approach to weir construction is to employ standard Jersey Barrier sections. Standard Maine DOT weir dimensions are used and notch width is calculated as detailed elsewhere in this report.

When esthetic considerations are important, weirs can be constructed of natural materials, e.g., logs on a stone foundation in smaller streams; weirs on larger streams may be constructed of rock. The simplest weir extends straight across the stream; alternative plan forms are V-shaped, pointing up or down stream. The log ends should be anchored to stone or block on the stream bank and keyed into the bank. The banks in the vicinity of the log ends should be riprapped to prevent scour and channel migration at higher flow. The foundation stones should be sized to withstand the 100-year flood and wrapped in geofabric so that they stand as a unit, thereby achieving additional stability. The wrap also seals the log structure and forces more of the water over the weir or through the spillway, rather than between the logs. The logs can be stacked vertically or angled downstream; angling creates quiescent water beneath the crest where fish can rest. The weir should be square-notched, according to the idea that fish will be attracted to and pass through the water spilling through the notch. The notch should be sized to flow full at the design passage flow using methods fully described below. Details for a log weir (grade control) structure (i.e., weir) is shown in Figures 4 and 5.

External (downstream) weirs signify additional maintenance responsibilities for Maine DOT. Weirs can create access and right-of-way issues, especially when a series of weirs is needed to obtain the necessary tailwater. With typical inter-weir spacing of 10 ft – 16.5 ft (3 m – 5m), several weirs will probably extend beyond existing right-of-way and thus may not be a practical solution. If additional drainage easement cannot be obtained, in-culvert weirs should be considered for larger pipes ($D \geq 5$ ft (1500 mm)).

As noted generally for culvert end treatments, the use of rock riprap should be controlled so as not to induce heating of water.

Figure 4: Log Drop Control Structure

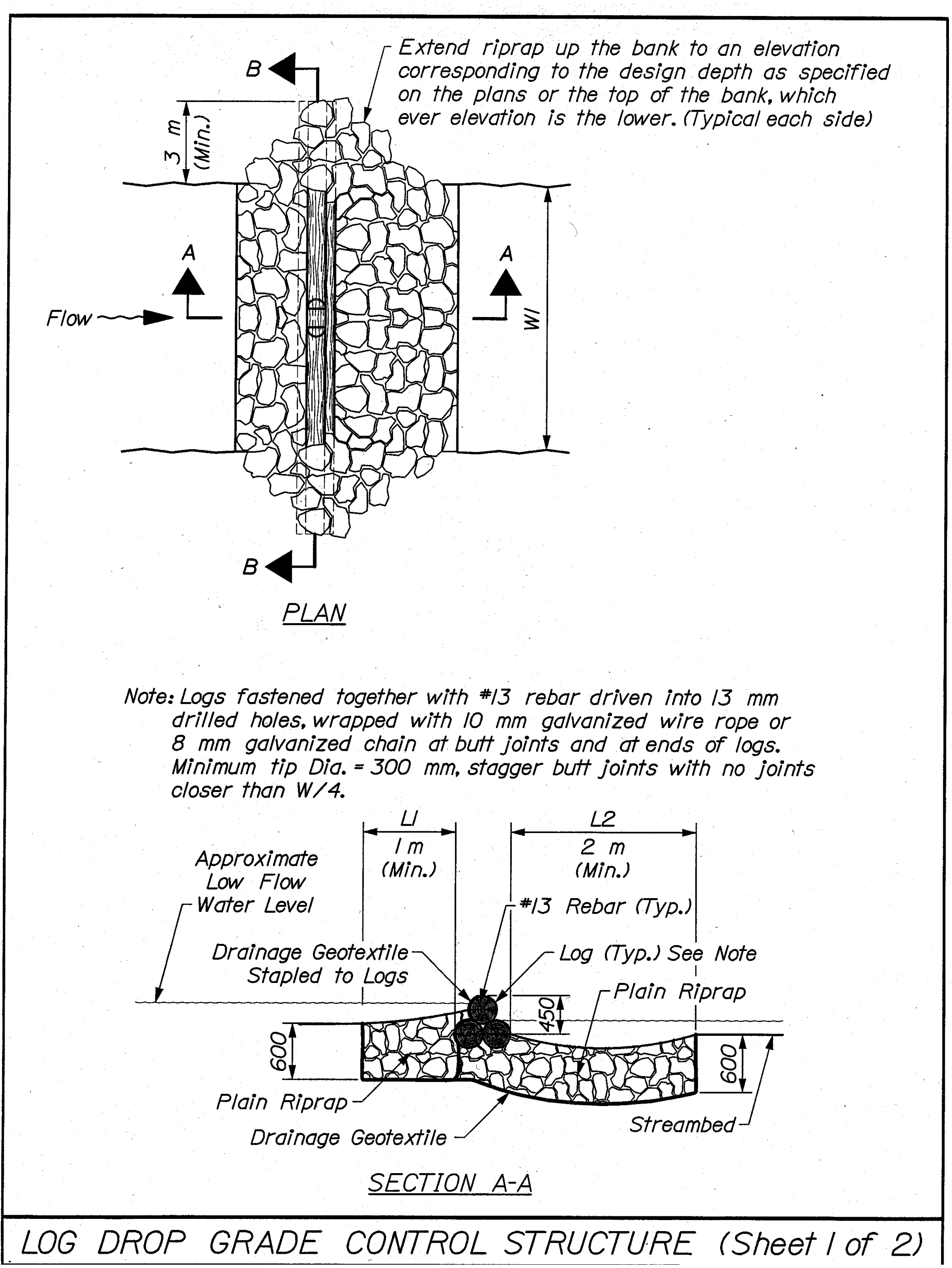
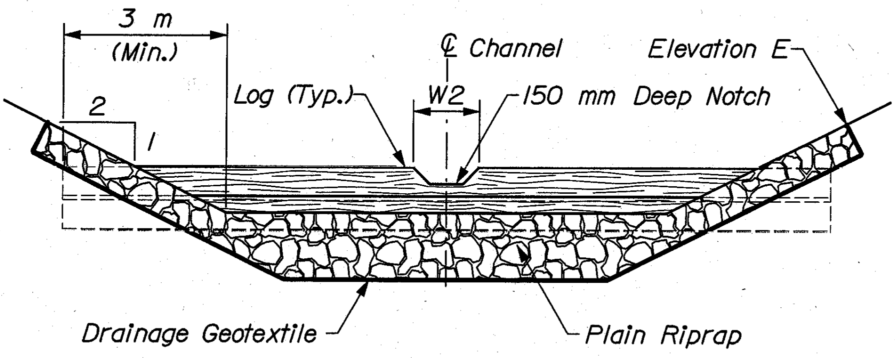


Figure 5: Log Drop Control Structure (cont.)

NOTE: 1.) Channel Width (W1) as specified on the Plans.
2.) Notch Width (W2) as specified on the Plans.
3.) Upstream Length (L1) as specified on the Plans.
4.) Downstream Length (L2) as specified on the Plans.
5.) Top of Riprap Elevation (E) as specified on the Plans.

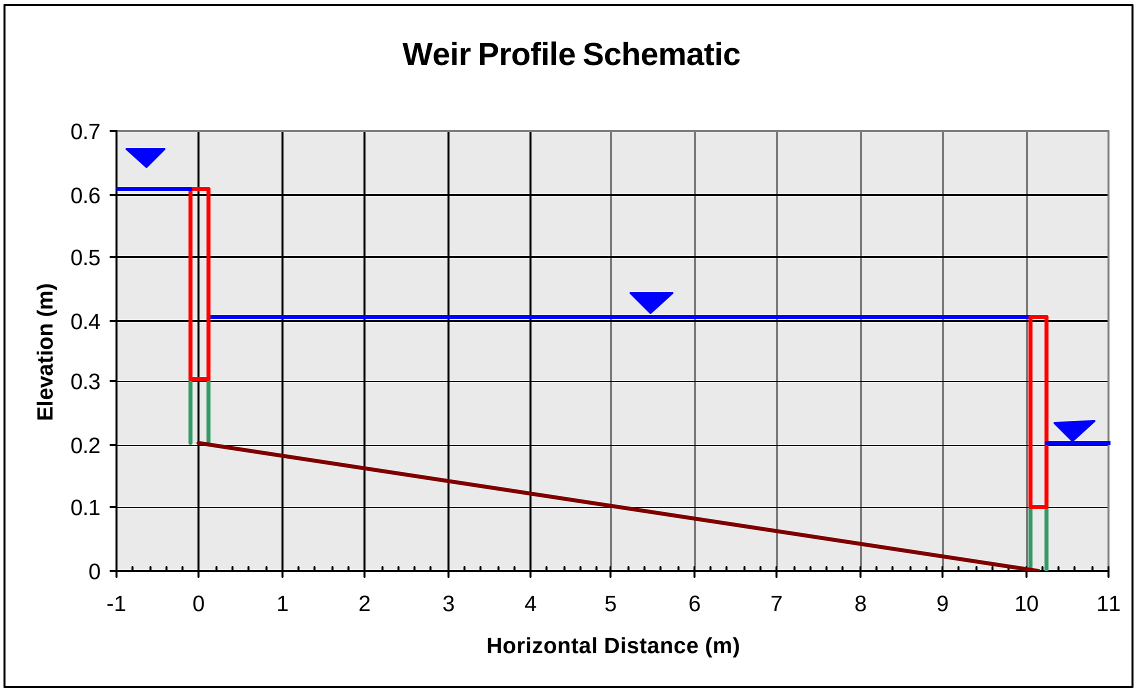


SECTION B-B

LOG DROP GRADE CONTROL STRUCTURE (Sheet 2 of 2)

In-Culvert Grade Control: Culverts with Weirs

Weirs are added to the interior of a culvert to create adequate water depths at low flows and limit regions of high velocity. They create a series of pools inside the culvert, the effect being increased water depth and reduced velocity to permit fish to move up through the pipe. Such a modified culvert constitutes a type of "weir and pool" fishway. Maine DOT will use rectangular notched weirs in these situations. Due to constructability issues, in-culvert weirs are limited to larger culverts (D generally ≥ 5 ft).



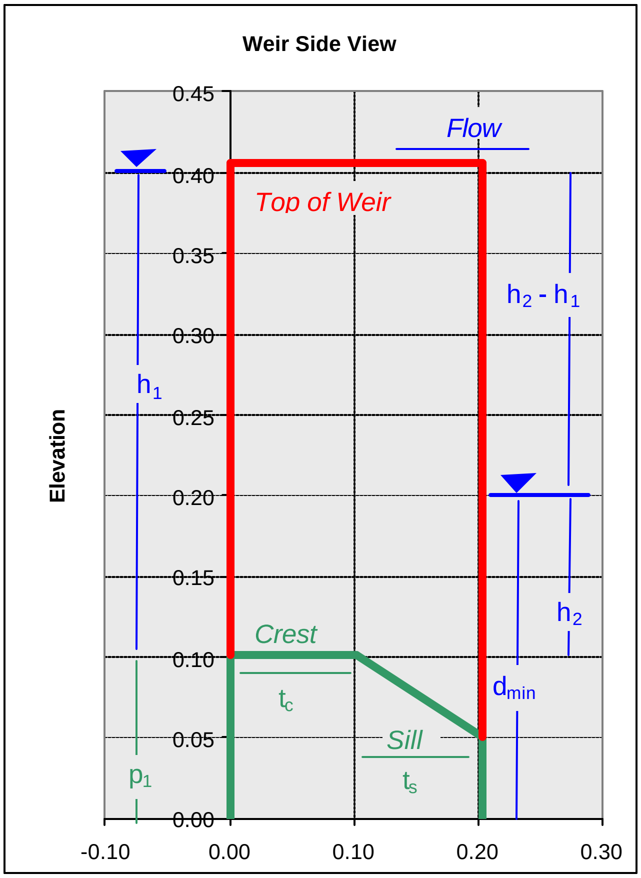
Weir Design

The objective in weir design is to pass the specified design flow while maintaining the necessary depth of water behind the weir. The shallowest depth in a weir-pool sequence in a culvert of simple uniform slope is at the downstream base of a weir. Most weir dimensions will be specified as design standards, leaving the inter-weir spacing and weir notch width as the principal parameters to be determined according to specific site topographic and hydrologic conditions and species requirements. The inter-weir spacing will typically be determined by the culvert slope and the specified drop in pool elevation. The notch width is a function of the design flow and the other specified weir dimensions.

Weir Specifications

A schematic of a section across the weir is shown below with dimensions indicated; a frontal view is given on the following page. The “crest” is synonymous with the “notch”. Most weir dimensions will be standardized as listed here. The following specifications should be observed, unless the design flow, pipe size, or construction issues indicate otherwise.

- Notch shall be at least 12 inches (300 mm) deep (h_1), from top of weir contraction to notch crest
- Notch shall be submerged by 4 inches (100 mm) in the downstream pool to enable passage by non-jumping fish (h_2)
- Drop between pool elevation across weir shall be 8 inches (200 mm) ($h_1 – h_2$)
- Crest shall be 4 in (100 mm) thick (t_c)
- Beveled sill shall be at least 4 in (100 mm) thick (t_s)
- Notch shall be rectangular, beveled in the downstream direction with a sill slope (H:V) = (2:1)
- Distance from notch crest to base shall be at least 4 inches (100 mm) (p_1)

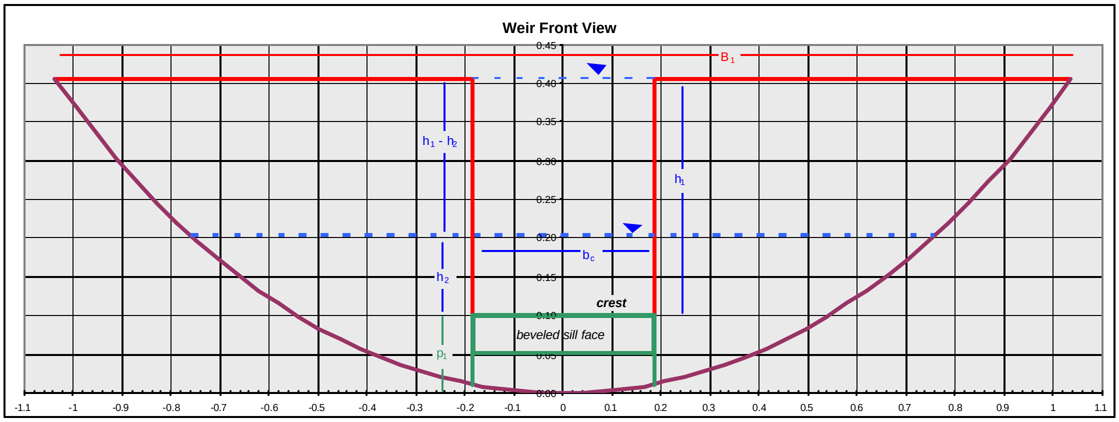


Required Depth of Water

Strictly speaking, the required depth of water depends on the species of interest and time of movement. In the interest of simplifying the design process, MDOT will generally use a design depth of 8 inches (200 mm) at the shallowest point in a pool between weirs. A particular situation may warrant using a different value, based on the fish data in Table 2 of the Fish Passage Policy.

Drop Between Pools

The drop ($h_1 – h_2$) in water surface elevation between pools should be set according to the species of interest, depending on the ability of a fish to jump between pools. In the interests of developing a robust design suitable for a variety of species, Maine DOT will design for an 8 inch (200 mm) drop between pool elevations unless particular circumstances suggest otherwise. Since the weirs are dimensioned to be partially submerged at the design flow, both jumping and non-jumping species should be able to navigate the weir notch. Appendix 1B of the Fish Passage Policy provides the detailed information useful for alternative individual design standards.



Inter-Weir Spacing

Spacing between weirs depends on the culvert slope and the specified drop between water pools across weirs. In general, the maximum spacing is calculated according to the simple geometric relationship

$$L_w = \Delta h / S$$

where L_w = nominal spacing between weirs = pool length
Δh = drop in water surface elevation between pools
S = culvert slope

The minimum spacing between weirs is 6.5 ft (2 m).

The calculated inter-weir spacing should be interpreted as the maximum allowable spacing. The actual final design spacing may be something less than the nominal calculated value; other design and habitat issues may indicate a smaller value as being more appropriate. When concrete pipe sections with prefabricated weir units are used, select a combination of sections that will give the largest weir spacing that does not exceed the calculated value. The weir and crest elevations should be checked when something other than the initial calculated spacing is elected. The first weir should be placed at the culvert outlet.

Weir Notch Width Calculation

The weir notch depth h_1 is fixed by the specified crest submergence h_2 (usually 4 in or 100 mm) and the pool drop ($h_1 - h_2$; usually 8 in or 200 mm). This leaves the notch width b_c as the weir parameter designed to accommodate the fish passage flow. The notch width is calculated using the Kindsvater-Carter sharp-crested weir equation:

$$Q = C_e b_e (2/3)(2g)^{1/2} h_e^{3/2}$$

where

Q = flow passed by freely flowing (i.e., not submerged) weir
b_e = effective notch width = $b_c + K_b$
K_b = notch width correction (tabulated function)
b_c = actual notch width
C_e = effective discharge coefficient (tabulated function)
g = acceleration due to gravity (32.2 ft/s^2; 9.81 m/s^2)
h_e = effective head = h_1 + 0.003 ft (0.001 m)
h_1 = upstream water surface elevation referenced to crest elevation

This equation can be quite accurate when calibrated for carefully constructed sharp-crested weirs used in flow-measurement situations. However, culvert weirs will not be built as "true" sharp-crested weirs and there is also significant uncertainty in the design flow estimates. Therefore, the correction for effective head (0.003 ft) can be ignored and h_1 used in place of h_e. The notch width correction K_b is a tabulated empirical function (see Appendix 2B). Again, it is a very small number ($-0.003 \text{ ft} < K_b < 0.016 \text{ ft}$) compared to expected notch widths (b_c typically > 1 ft) and so can be ignored. The effective discharge coefficient C_e is a function of the notch width-channel width ratio (b_c/B_1) and above crest–below crest depth ratio (h_1/p_1). This functional dependence on b_c must be accounted for in the solution for b_c. This function is also tabulated in Appendix 2B. Employing the suggested approximations, the weir equation becomes

$$Q = C_e b_c (2/3)(2g)^{1/2} h_1^{3/2}$$

The fish pass weirs will be designed to flow partially submerged at design discharges, in order to pass both jumping and non-jumping species. A submerged weir will pass less water than a freely flowing weir, all other things being equal. Therefore, a weir designed for submerged flow must have a larger opening to pass the hydrologic design flow. The submergence correction factor r_s is determined following the method of Villemonte:

$$r_s = \{1 - (h_2/h_1)^{3/2}\}^{0.385} = (Q/Q_{free}) \qquad \leq 1$$

where h_1 and h_2 are the respective upstream and downstream pool elevations above the weir crest, Q is the actual flow expected (by hydrology/hydraulics analysis), and Q_{free} is the flow through a freely discharging weir of the same dimensions. Maine DOT in-culvert weirs will usually be designed with 4 inch submergence (h_2 = 4 in or 100 mm). The effect of partial submergence is to reduce the flow over the weir. Therefore, the nominal design free flow must be increased over the actual hydrologic flow needed over the weir:

$$Q_{free} = Q/r_s$$

The weir is sized according to Q_{free} (= Q/r_s); the actual flow Q is chosen according to watershed hydrology and the flows prevailing during periods of fish movement.

Solving for the design notch width gives

$$b_c = \{Q/r_s\}/\{C_e(2/3)(2g)^{1/2}h_1^{3/2}\}$$

This is actually a non-linear equation in b_c, since the discharge coefficient C_e is a function of b_c. Several iterations will be needed to solve for b_c, using the above equation in conjunction with Appendix 2B.

Design Procedure

The design procedure for in-culvert weirs is fairly simple and consists of five steps:

1. estimate a design flow Q according to watershed hydrology and/or channel hydraulics and target species period of movement. If not performing a detailed channel-specific or species-specific analysis, use the average of the September and October median flows (see Appendix 2A).
2. calculate the nominal distance between weirs based on culvert slope and drop in water surface elevation between weirs. Set final spacing according to constructability requirements so as not to exceed nominal calculated value.
3. assign weir dimensions and auxiliary hydraulic design parameters. Use the values given under "Weir Specifications" above as starting values; they may have to be revised in the process of developing a final design.
4. calculate nominal weir notch (crest) width according to Kindsvater-Carter sharp-crested weir equation.
5. set final notch width according to constructability requirements.
6. check final design value for compliance with needed minimum pool depth.

Design Example

A 10-ft culvert under a deep fill has been identified as needing attention. Whatever approach is taken, passage for trout must be provided. After evaluating several alternatives, concrete invert lining has been identified as the best choice. Design a pool-weir arrangement to pass fish.

Watershed and culvert data are summarized in the following table:

Watershed		**Culvert**	
Area	12 mi^2 (31.1 km^2)	Diameter	10 ft (3000 mm)
NWI area	24.8%	Slope	2%
Sand & gravel aquifer	0 %	Length	60 ft
Avg annual precip	44.2 in (1123 mm)	Roughness n	0.024 (CMP)
Distance to coast	41.6 mi (67.4 km)		

Fish Requirements

Based on Appendix 1B in the Fish Passage Policy, trout are moving from April through November, though passage is not critical in the warm-water months of July and August. Flows in the September and October are the lowest flows in the months of interest and therefore provide the basis of a conservative design. The average of the September and October medians will be used, with the understanding that such a design will deliver the needed depths at the other, higher, flows.

Maine DOT generic design is to provide a minimum of 8 in depth when possible. Trout have a typical maximum body thickness of 4 in (100 mm), indicating a minimum depth for passage of (1.5 x 4 in) = 6 in (150 mm). In a sloping culvert, the minimum depth between weirs occurs at the base of the upper weir. Therefore, initial design will be for a depth d_{min} = 8 in (200 mm) at the downstream side of a weir.

Trout are capable of jumping, so strictly speaking, the weir does not have to be designed for submergence. However, Maine DOT general practice is to partially submerge the weir crest to facilitate passage of non-jumping species. Therefore, initial design will be for the downstream pool to be h_2 = 4 in (100 mm) above the weir crest.

Design Flow

Design flows can be based on field observations (actual depth/velocity measurements during the period of interest; minimum channel sections needed for movement) or median flow equations for the periods of movement. Using the watershed data, monthly median flows were estimated using the U.S. Geological Survey regression equations. The September and October flows can be calculated using the equations in Appendix 2A, by look-up in the charts in Appendix 2A, or using the Maine DOT monthly median flow Excel worksheet.

By chart look-up, the average of the September and October medians is

$$\begin{aligned} Q &= (Q_{Sep} + Q_{Oct})/2 \\ &= 3.5 \text{ ft}^3/\text{s} = 0.100 \text{ m}^3/\text{s} \end{aligned}$$

This hydrologic design value will need to be adjusted for the specified submergence condition.

Weir Dimensions and Auxiliary Hydraulic Design Specifications

Recommended design values for water levels are

$h_1 - h_2$ = 8 in (0.667 ft = 200 mm) change in pool elevation across weir
h_2 = 4 in (0.333 ft = 100 mm) downstream submerged depth on crest

It follows that the upstream depth on the weir crest is

$$h_1 = (h_1 - h_2) + h_2 = 12 \text{ in } (1 \text{ ft} = 300 \text{ mm})$$

The height p_1 of the weir crest above the culvert invert is

$$p_1 = d_{min} - h_2 = 8 - 4 = 4 \text{ in } (0.333 \text{ ft} = 100 \text{ mm})$$

and the pool depth d_1 just upstream of the weir is

$$d_1 = h_1 + p_1 = 16 \text{ in } (1.333 \text{ ft} = 400 \text{ mm}).$$

The submergence ratio r_s is

$$r_s = \{1 - (h_2/h_1)^{3/2}\}^{0.385} = 0.921 = (Q/Q_{free})$$

The weir will actually be designed to accommodate a freely discharging flow of

$$Q_{free} = Q/r_s = (3.5 \text{ ft}^3/\text{s})/0.921 = 3.8 \text{ ft}^3/\text{s } (0.108 \text{ m}^3/\text{s})$$

Spacing Between Weirs

Spacing is calculated as

$$L_w = \Delta h/S$$

Where Δh = difference pool elevation across a weir and S is the culvert slope.

$$L_w = (0.667 \text{ ft})/0.02 = 33.35 \text{ ft } (10.2 \text{ m})$$

Calculate Notch Width

The notch width b_c is calculated with the Kindsvater-Carter sharp-crested weir equation. The pipe is flowing partially full at flows characteristic of fish passage. The pool surface top width in a circular culvert just upstream of the weir is

$$B_1 = 2\{d_1(D - d_1)\}^{1/2} = 6.8 \text{ ft} = 2073 \text{ mm}$$

as calculated for a partially-flowing circular pipe. If a different culvert shape is used, then a different equation for B_1 should also be used.

The weir equation, rearranged for crest (notch) width b_c is

$b_c = \{Q/r_s\}/\{C_e(2/3)(2g)^{1/2}h_1^{3/2}\}$

The discharge coefficient C_e is determined using the chart in Appendix 2B. The depth ratio h_1/p_1 is (12 in/4 in) = 3. The width ratio b_c/B_1 is actually part of the solution for b_c and so an initial estimate must be made. Assume a b_c starting value ½ of the upstream pool width B_1, so initial $b_c = 3.4$ and $b_c/B_1 = 0.5$. By chart look-up, $C_e = 0.63$. Then

$$b_c = \{3.8\ ft^3/s\}/\{0.63(2/3)(2 \times 32.2\ ft/s^2)^{1/2}(1\ ft)^{3/2}\}$$
$$= 1.13\ ft = 0.34\ m$$

The assumed initial width ratio should be checked with this first iteration solution:

$b_c/B_1 = 1.13\ ft/6.8\ ft = 0.17$ (compare to initial value 0.5)

Since this new value is so different from the initial assumption, the solution should be repeated. The new corresponding C_e value is 0.59 (for $h_1/p_1 = 3$, unchanged)

$$b_c = \{3.8\ ft^3/s\}/\{0.59(2/3)(2 \times 32.2\ ft/s^2)^{1/2}(1\ ft)^{3/2}\}$$
$$= 1.20\ ft = 0.37\ m$$

$b_c/B_1 = 1.2/6.8 = 0.18$ (compare to previous 0.17; 5% difference)

Given the uncertainty and approximation inherent in the various assumptions, this result is acceptable. Make the weir notch 1.2 ft (0.37 m) wide.

This same example is carried through in the worksheet that follows. This worksheet utilizes the additional correction K_b for the notch width. Designers can utilize the "manual" worksheet in Appendix 2C or the Maine DOT Excel worksheet for weir sizing calculations.

Design Example

Fish Passage Weir-and-Pool Design Worksheet

Watershed Characteristics and Design Flow

1	Area (A)	12	sq miles
2	Sand & Gravel Fraction (SG)	0	Decimal fraction of area
3	Design Flow Q	3.5	ft^3/s

Note: sand & gravel values only needed for monthly median flow equations; other design flow estimation methods may be used.

Weir, Culvert and Hydraulic Specifications

(perform all calculations in consistent units of feet or meters)

1	$h_1 - h_2$	8 in = 0.667 ft	W.L. drop across weir
2	h_2	4 in = 0.333 ft	Submerged depth on weir
3	d_{min}	8 in = 0.667 ft	Min pool depth (downstream base of weir)
4	D	10 ft	Pipe diameter
5	S	0.02	Culvert slope
6	h_1	*4* + *8* = 12 in = 1 ft	Upstream depth on weir $h_2 + (h_1 - h_2)$
7	p_1	*8* – *4* = 4 in = 0.333 ft	Height of weir crest above invert $d_{min} - h_2$
8	d_1	*4*+*12* = 16 in = 1.333 ft	Upstream pool depth $h_1 + p_1$
9	r_s	$\{1-(0.333/1)^{1.5}\}^{0.385}$ = 0.921	Submergence ratio $\{1-(h_2/h_1)^{3/2}\}^{0.385}$
10	B_1	$2\{1.333(10-1.333)\}^{1/2}$ = 6.8 ft	Pool top width at weir $2\{d_1(D - d_1)\}^{1/2}$
11	L_w	*0.667 ft/0.02* = 33.35 ft	Weir spacing $(h_1 - h_2)/S$
12	Q/r_s	3.8 ft^3/s	Design flow adjusted for submergence Q/r_s

Calculations for Notch Width

Computation Constants

1	(Q/r_s)	3.8	from above
2	$(2/3)(2g)^{1/2}$	5.35	5.35 $ft^{1/2}/s$; 2.95 $m^{1/2}/s$
3	$h_1^{3/2}$	$1^{3/2} = 1$	h_1 from above
4	$A = (Q/r_s)/\{(2/3)(2g)^{1/2}h_1^{3/2}\}$	0.71	Computation constant A
5	B_1	6.8	Pool width B_1 from above
6	h_1/p_1	1/0.333 = 3	Above crest-below crest depth ratio

Iteration for Notch Crest Width b_c

Iteration	0	1	2	3	4	5	6	7
b_c/B_1		0.5	0.16	0.18				
K_b		0.01	0.01	0.01				
C_e		0.63	0.58	0.58				
$b_e = A/C_e$		1.13	1.22	1.22				
$b_c = b_e - K_b$	3.4	1.12	1.21	1.21				

Notes:

- *always use consistent units of [feet] or [meters] in hydraulic calculations*
- *set initial (iteration 0) b_c value = ½ of B_1;*
- *get K_b and C_e by look-up in Appendix 2B;*
- *iterate until crest width b_c stops changing*
- *blank version of this worksheet in Appendix 2C*

Downstream Weirs (Grade Control Structures)

When a culvert outlet is excessively perched, downstream grade control may be needed to allow fish entry into the culvert. As a practical matter, right-of-way considerations may severely limit such options. That said, two types of weirs should be considered: rectangular notch weir as described for in-pipe applications; and full channel-width broad-crested weir.

Rectangular Notch Weir

The rectangular notch weir is sized in the same way as for in-pipe weirs. Different methods of construction will be used, though. An approach with great promise is to use sections of Jersey Barrier as the basic building blocks of the weir.

Broad-Crested Weir

The broad-crested weir is in many cases the gravel push-bar at the exit of the culvert outlet pool. The bar extends fully across the channel . The length (in direction of flow) of the bar is long compared to the depth of water on the bar. The effect is to induce critical flow over the bar. A conservative approach is to simply set the bar elevation at the nominal desired water surface elevation at the culvert outlet. However, this will actually produce a water surface elevation higher than nominal design, since it ignores the depth of flow over the bar.

The bar flow depth can be accounted for by using the broad-crested weir equation:

$$Q = C_d(2/3)(2g/3)^{1/2} b_c h_1^{3/2}$$

where C_d = discharge coefficient (0.9 assumed)
b_c = channel width across the bar
h_1 = water elevation upstream of bar (referenced to bar elevation)

There are a variety of equations and charts available for determining C_d. However, in view of the uncertainty and variability inherent in the weirs contemplated here, it suffices to use a standard value of 0.9. Solving for h_1 gives the necessary elevation of the bar below the desired water surface elevation:

$$h_1 = [Q/\{C_d(2/3)(2g/3)^{1/2} b_c\}]^{2/3}$$

This function is illustrated below for a range of weir widths. This correction is best used for larger watersheds and design flows or where design refinement is needed to solve particular site problems.

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Appendix 2A

Regression Equations for Monthly Median Flows in Maine Rivers and Streams

Based on

Estimating monthly, annual, and low 7-day, 10-year streamflows for ungaged rivers in Maine

U.S. Geological Survey Scientific Investigations Report 2004-5026

by

R.W. Dudley
U.S. Geological Survey
Augusta, Maine
2004

Regression equations and their accuracy for estimating monthly median streamflows for ungaged, unregulated streams in rural drainage basins in Maine.

	Measures of Accuracy		
Regression equation	ASEP (in percent)	$(PRESS/n)^{1/2}$ (in percent)	Average EYR
$Q_{\text{jan median}} = 20.71\,(A)^{1.036}\,(DIST)^{-0.762}$	-16.1 to 19.2	-17.3 to 20.9	8.87
$Q_{\text{feb median}} = 36.54\,(A)^{1.017}\,(DIST)^{-0.890}$	-13.4 to 15.5	-14.9 to 17.5	17.5
$Q_{\text{mar median}} = 183.7\,(A)^{0.999}\,(DIST)^{-1.142}$	-16.9 to 20.4	-19.0 to 23.5	13.3
$Q_{\text{apr median}} = 0.227\,(A)^{1.010}10^{0.028(pptA)}$	-20.8 to 26.2	-22.0 to 28.3	3.75
$Q_{\text{may median}} = 0.262\,(A)^{1.070}\,(DIST)^{0.461}$	-20.4 to 25.6	-21.0 to 26.6	3.92
$Q_{\text{jun median}} = 0.734\,(A)^{1.076}$	-22.5 to 29.0	-23.6 to 30.8	4.26
$Q_{\text{jul median}} = 0.210\,(A)^{1.149}10^{1.02(SG)}$	-26.1 to 35.4	-27.3 to 37.5	3.58
$Q_{\text{aug median}} = 0.152\,(A)^{1.120}10^{1.31(SG)}$	-28.6 to 40.2	-29.6 to 42.1	3.86
$Q_{\text{sep median}} = 0.169\,(A)^{1.093}10^{1.25(SG)}$	-26.8 to 36.7	-27.8 to 38.5	5.37
$Q_{\text{oct median}} = 0.307\,(A)^{1.074}10^{1.11(SG)}$	-25.8 to 34.8	-30.0 to 43.0	8.28
$Q_{\text{nov median}} = 1.222\,(A)^{1.004}$	-28.9 to 40.6	-30.6 to 44.1	4.39
$Q_{\text{dec median}} = 12.00\,(A)^{1.000}\,(DIST)^{-0.513}$	-13.1 to 15.0	-14.6 to 17.1	21.6

ASEP — average standard error of prediction

PRESS — prediction error sum of squares

EYR — equivalent years of record

Q — streamflow statistic of interest.

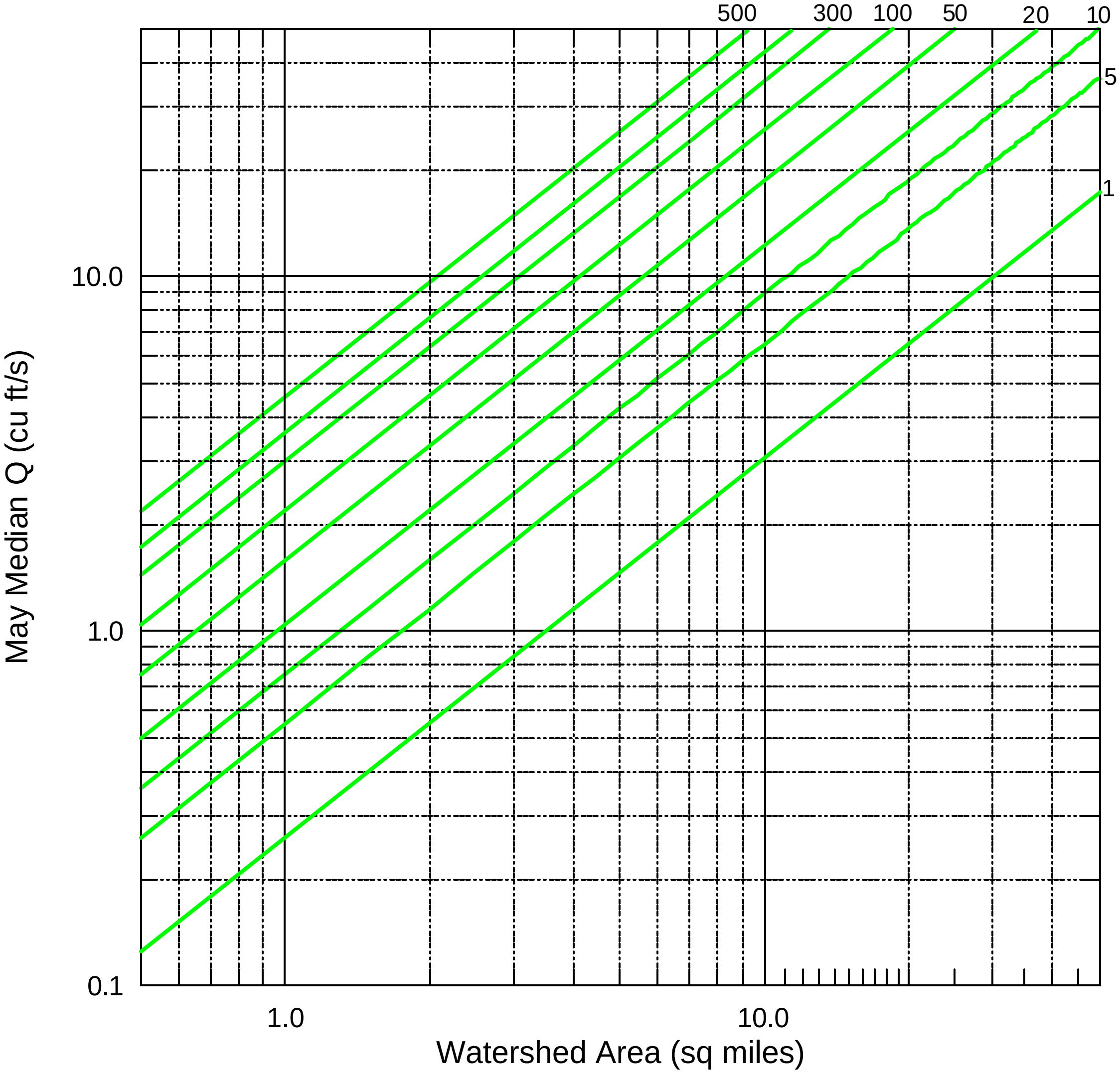
A — contributing drainage area, in square miles.

SG —fraction of the drainage basin that has significant sand and gravel aquifer, on a planar area basis, expressed as a decimal. For example, if 15% of a basin's drainage area has significant sand and gravel aquifers, SG = 0.15. Based on the significant sand and gravel aquifer maps produced by the Maine Geological Survey and maintained as GIS data sets by the Maine Office of GIS.

pptA — mean annual precipitation, in inches, computed as the spatially averaged precipitation in the contributing basin drainage area. Based on non-proprietary PRISM precipitation data spanning the 30-year period 1961-1990. Data maintained as GIS data sets by the United States Department of Agriculture (1998).

DIST —distance from the coast, in miles, measured as the shortest distance from the contributing drainage basin centroid to a line in the Gulf of Maine. The line in the Gulf of Maine is defined by end points 71.0W, 42.75N and 65.5W, 45.0N, referenced to North American Datum (horizontal) 1983.

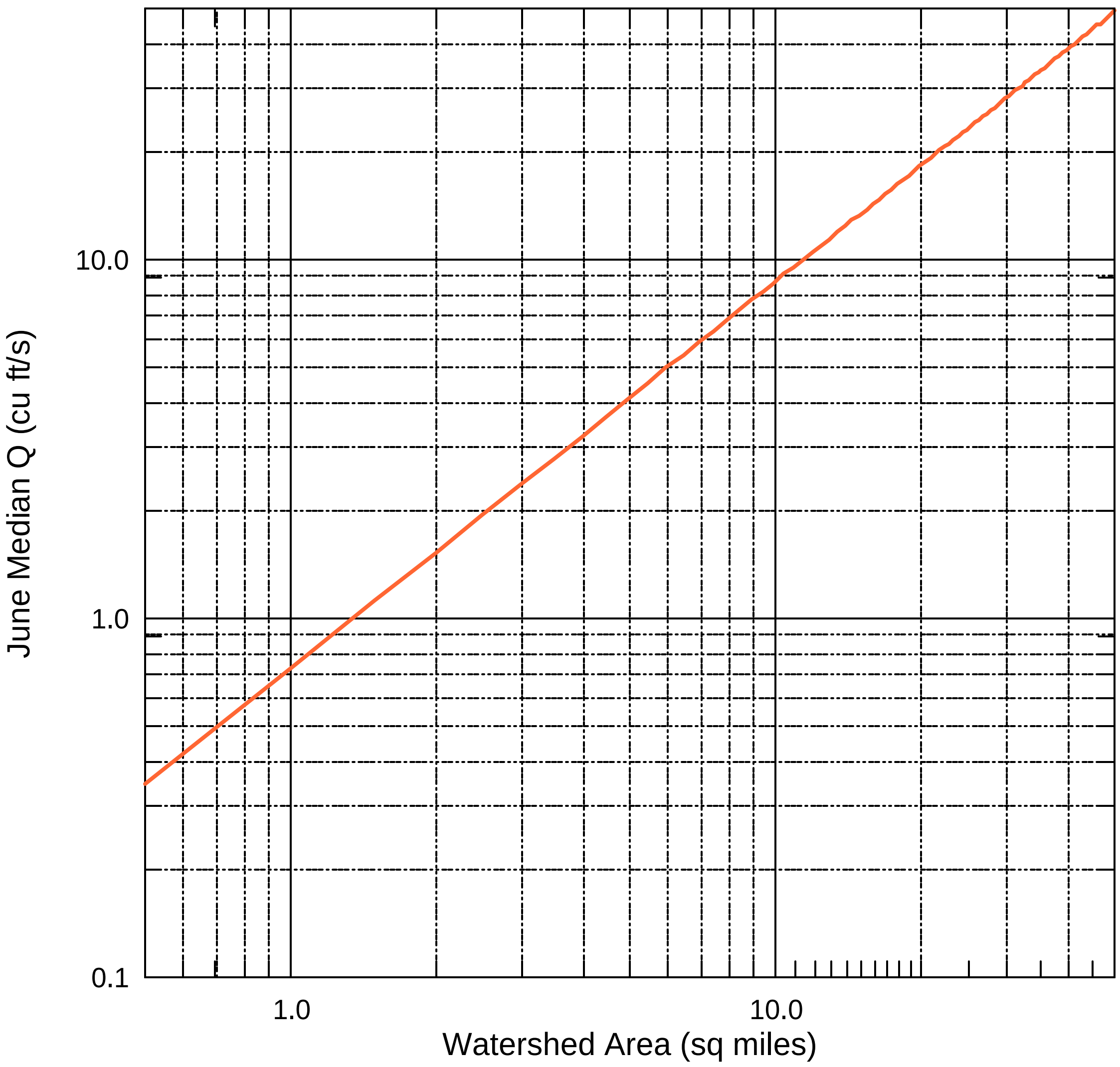
May Median Flows for Selected Distances from Coast



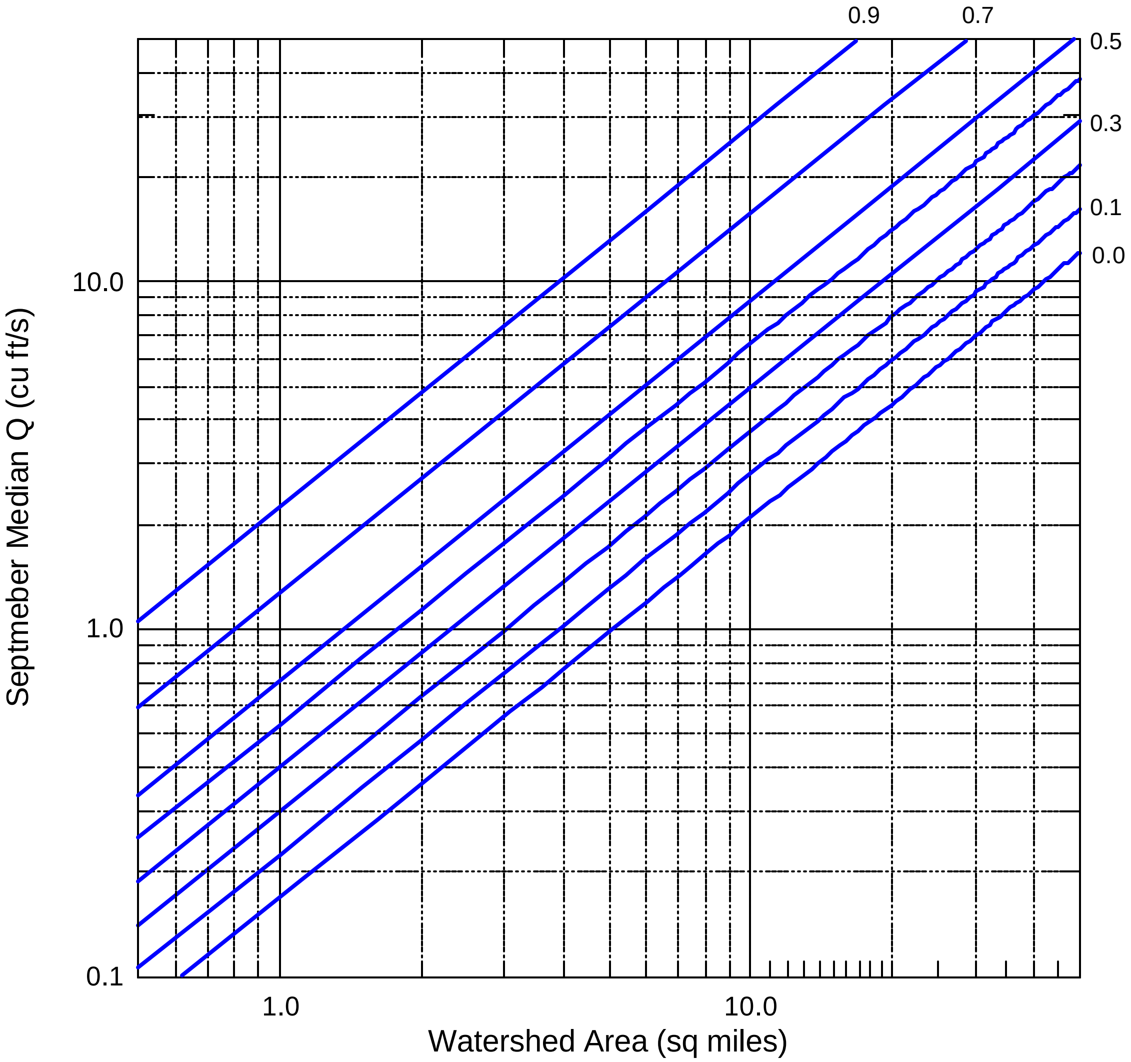
Distance is the DIST variable in the May regression equation, calculated as distance from the coast, in miles, from the watershed centroid point P_c to a line in the Gulf of Maine. The line in the Gulf of Maine is defined by lat-long endpoints P_1 (71.0W, 42.75N) and P_2 (65.5W, 45.0N), referenced to North American Datum (horizontal) NAD 1983. The corresponding UTM (zone 19, in meters) endpoint coordinates are P_1 (336321.28E, 4734992.89N) and P_2 (775853.73E, 4988911.83N). The point P_1 is the southwest endpoint and the point P_2 is the northeast endpoint of the reference line. DIST can be calculated using the following worksheet in UTM (metric) coordinates for the endpoints.

P_c		E		N	Watershed centroid (m, UTM)
P_1	336321.28	E	4734992.89	N	SW reference line endpoint
$\lvert P_1P_c \rvert$			$\{(P_{cE}-P_{1E})^2+(P_{cN}-P_{1N})^2\}^{1/2}$		Dist bet P_c and P_1 (m)
θ			$\mathrm{Tan}^{-1}\{(P_{cE}-P_{1E})/(P_{cN}-P_{1N})\} - 30.02^{o}$		Angle bet lines P_1P_c & P_1P_2
DIST			$\lvert P_1P_c \rvert \sin(\theta) / 1610$		Dist to reference line (miles)

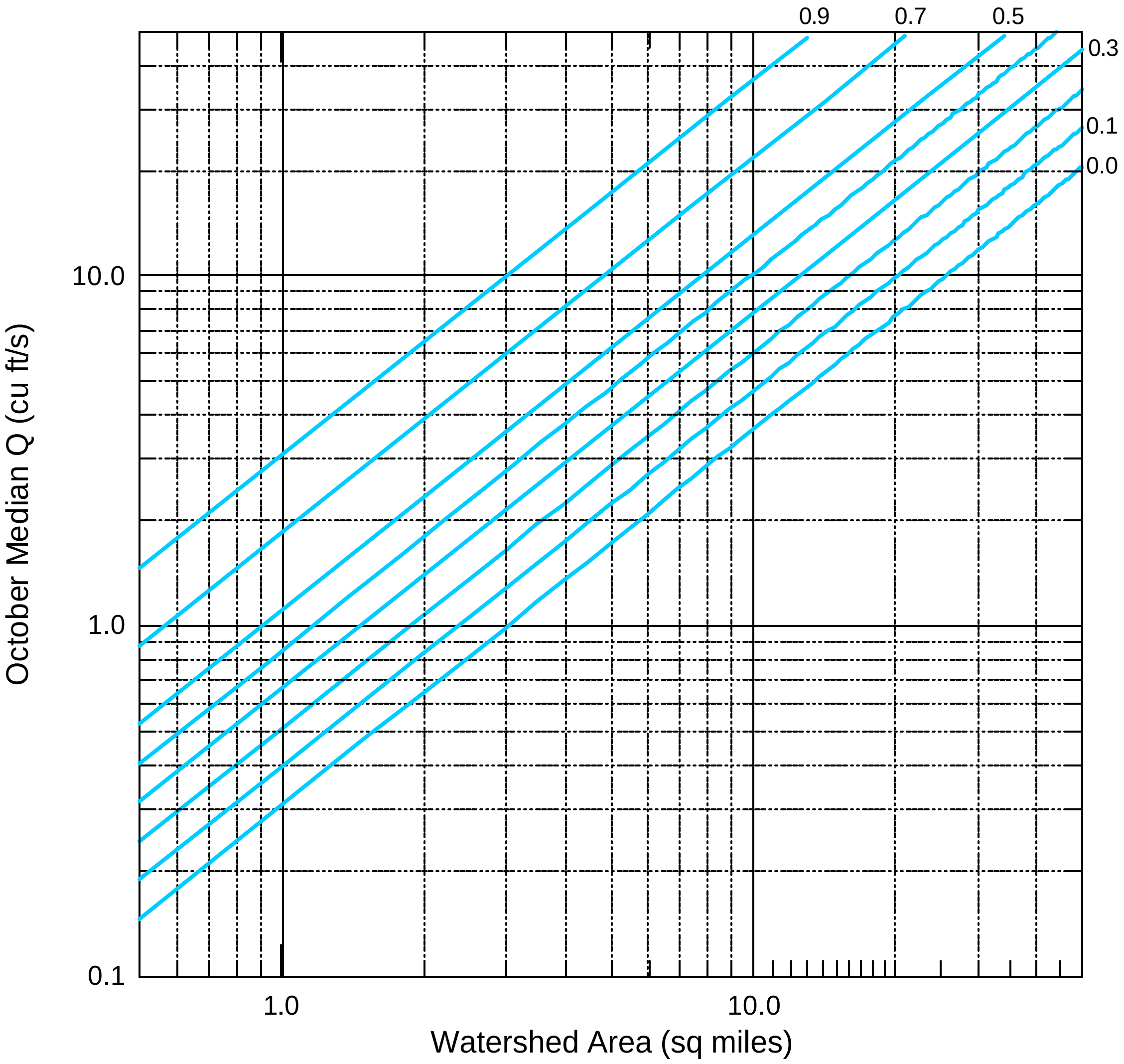
June Median Flows



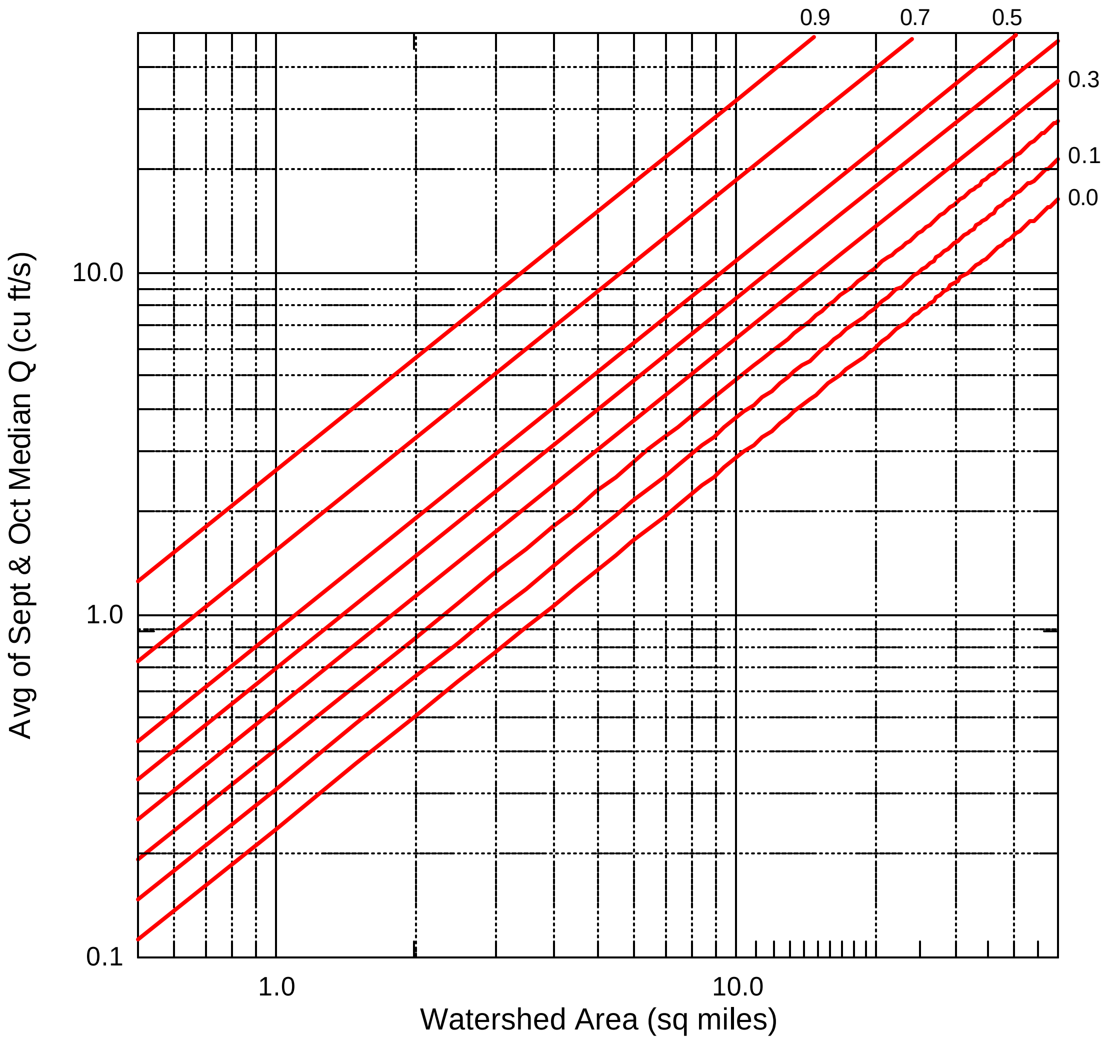
September Median Flows for Selected Sand & Gravel Fractions



October Median Flows for Selected Sand & Gravel Fractions



Average of September & October Median Flows for Selected Sand & Gravel Fractions



Project Name:	Example	**PIN:**	00000.00
Stream Name:	Any Stream	**Town:**	Anytown
Bridge Name:	Any Bridge	**Bridge No.**	0000
Route No.	Route 999	**USGS Quad:**	Any Quad
Analysis by:	CSH	**Date:**	2/3/2004

MAINE MONTHLY MEDIAN FLOWS BY USGS REGRESSION EQUATIONS (2004)

Worksheet prepared by:
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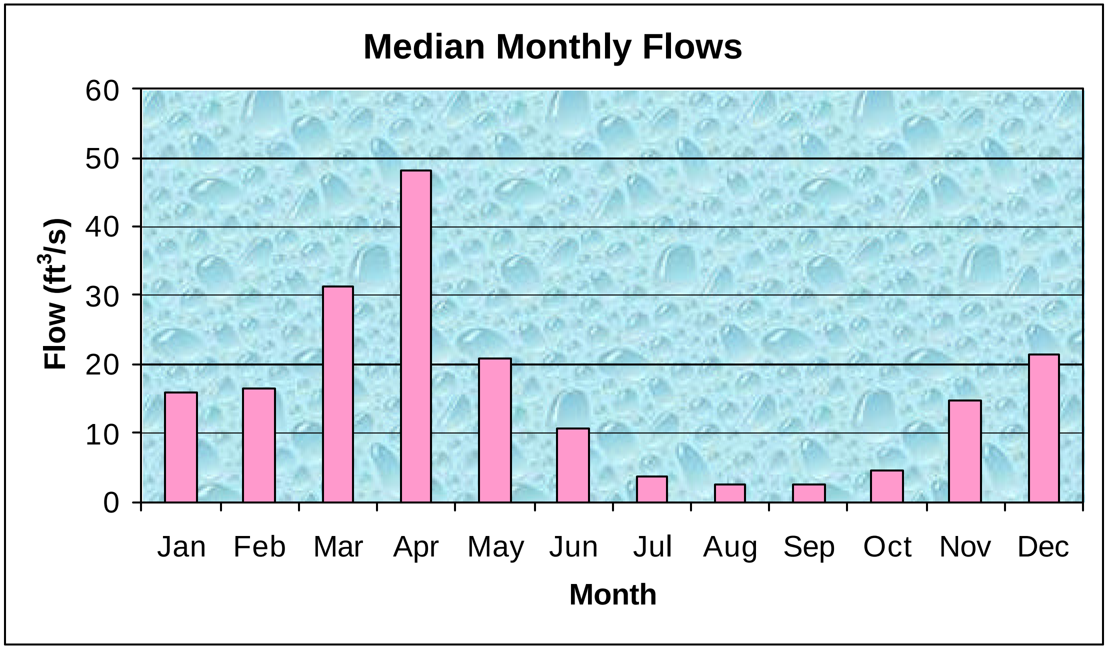
31.08

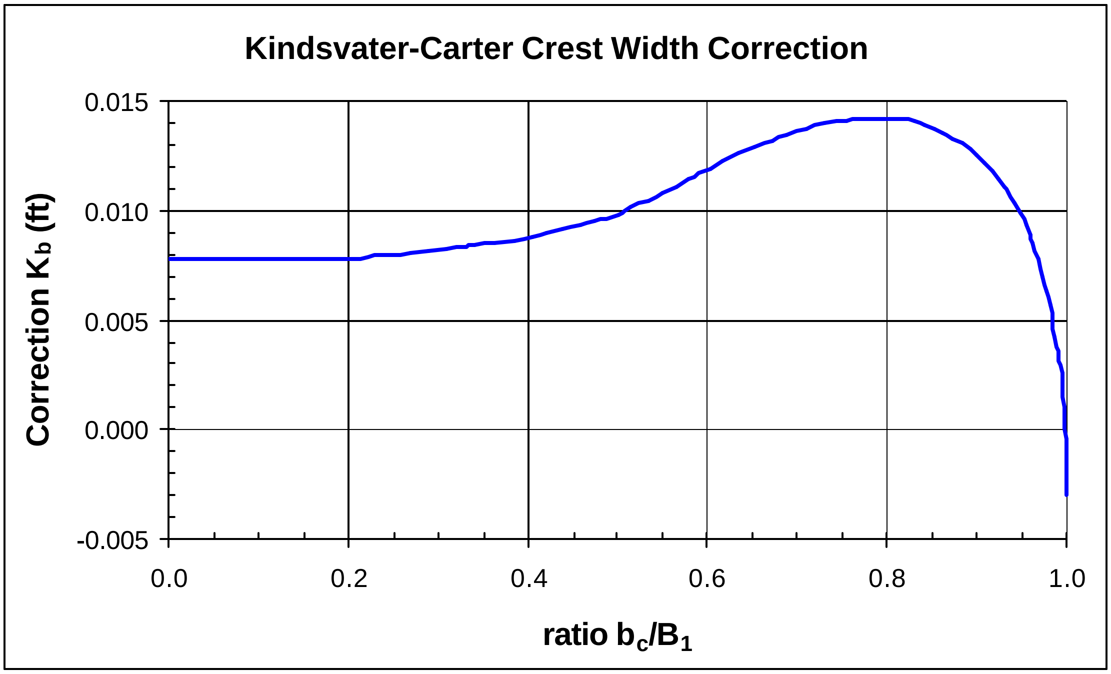
	Value	**Variable**	**Explanation**
	12	*A*	Area (mi^2)
625257	4979679	P_c	Watershed centroid (E,N; UTM; Zone 19; meters)
	41.57	*DIST*	Distance from Coastal reference line (mi)
	44.2	*pptA*	Mean Annual Precipitation (inches)
	0.00	*SG*	Sand & Gravel Aquifer (decimal fraction of watershed area)

Month	Q_{median} (ft3/s)
Jan	**15.88**
Feb	**16.58**
Mar	**31.16**
Apr	**48.26**
May	**20.86**
Jun	**10.64**
Jul	**3.65**
Aug	**2.46**
Sep	**2.56**
Oct	**4.43**
Nov	**14.81**
Dec	**21.28**

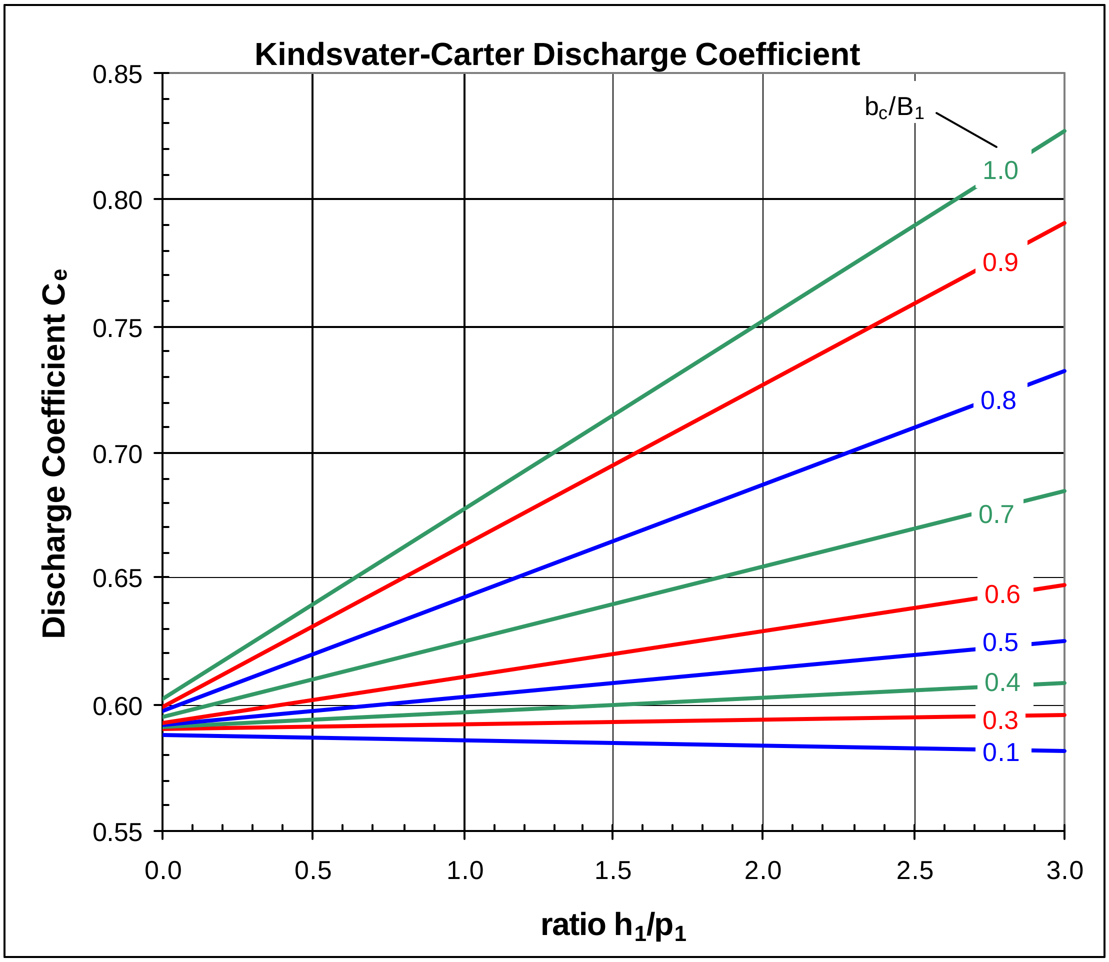


Appendix 2B

Coefficients for Kindsvater-Carter Sharp-Crested Weir Equation



Kindsvater-Carter Crest Width Correction					
b_c/B_1	K_b (ft)	K_b (m)	b_c/B_1	K_b (ft)	K_b (m)
0.00	0.0079	0.0024	0.80	0.0141	0.0043
0.20	0.0079	0.0024	0.82	0.0141	0.0043
0.25	0.0082	0.0025	0.84	0.0141	0.0043
0.30	0.0082	0.0025	0.86	0.0135	0.0041
0.35	0.0085	0.0026	0.88	0.0131	0.0040
0.40	0.0089	0.0027	0.90	0.0125	0.0038
0.45	0.0092	0.0028	0.92	0.0118	0.0036
0.50	0.0098	0.0030	0.94	0.0105	0.0032
0.55	0.0108	0.0033	0.96	0.0089	0.0027
0.60	0.0121	0.0037	0.98	0.0056	0.0017
0.65	0.0128	0.0039	1.00	-0.0030	-0.0009
0.70	0.0135	0.0041			
0.75	0.0141	0.0043			



Kindsvater-Carter Discharge Coefficient Equation Parameters

b_c/B	μ	β
0.0	-0.0023	0.587
0.1	-0.0021	0.588
0.2	-0.0018	0.589
0.3	0.0020	0.590
0.4	0.0058	0.591
0.5	0.0110	0.592
0.6	0.0180	0.593
0.7	0.0300	0.595
0.8	0.0450	0.597
0.9	0.0640	0.599
1.0	0.0750	0.602

Equation: $C_e = \mu(h_1/p_1) + \beta$

Appendix 2C

Worksheet for Rectangular Weir Notch Sizing

Project Name ____________________ PIN ________________
Stream Name ____________________ Town ________________
Route No. ____________________ Culvert No. ________________
Designer: ____________________ Date ________________

Maine Department of Transportation
Culvert Fish Passage Weir-and-Pool Design Worksheet

Watershed Characteristics and Design Flow

1	Area (A)	sq miles
2	Sand & Gravel Fraction (SG)	Decimal fraction of area
3	Passage Design Flow Q	ft^3/s

Note: sand & gravel values only needed for Sep and Oct monthly median flow equations; other design flow estimation methods may be used.

Weir, Culvert and Hydraulic Specifications

(perform all calculations in consistent units of feet or meters)

1	$h_1 - h_2$	Water level drop across weir
2	h_2	Submerged depth on weir
3	d_{min}	Min pool depth (downstream base of weir)
4	D	Pipe diameter
5	S	Culvert slope
6	h_1	Upstream depth on weir $h_2 + (h_1 - h_2)$
7	p_1	Height of weir crest above invert $d_{min} - h_2$
8	d_1	Upstream pool depth at weir $h_1 + p_1$
9	r_s	Submergence ratio $\{1-(h_2/h_1)^{1.5}\}^{0.385}$
10	B_1	Pool top width at weir $2\{d_1(D - d_1)\}^{1/2}$ *for circular culverts*
11	L_w	Weir spacing $(h_1 - h_2)/S$
12	Q	Design flow adjusted for submergence Q/r_s

Calculations for Weir Rectangular Notch Width

Computation Constants

1	(Q/r_s)	from above
2	$(2/3)(2g)^{1/2}$	5.35 $ft^{1/2}/s$; 2.95 $m^{1/2}/s$
3	$h_1^{3/2}$	h_1 from above
4	$A = (Q/r_s)/\{(2/3)(2g)^{1/2} h_1^{3/2}\}$	computation constant A
5	B_1	pool width B_1 from above
6	h_1/p_1	above crest-below crest depth ratio

Iteration for Notch Crest Width b_c

Iteration	0	1	2	3	4	5	6	7
b_c/B_1								
K_b								
C_e								
$b_e = A/C_e$								
$b_c = b_e - K_b$								

Notes: always use consistent units of [feet] or [meters] in hydraulic calculations
set initial (iteration 0) b_c *value = ½ of* B_1*;*
get K_b *and* C_e *by look-up in Appendix B;*
iterate until crest width b_c *stops changing*