Title

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Publication Date
2001-09-24

NATURAL FISH PASSAGE STRUCTURES IN URBAN STREAMS (PART 2: HYDRAULIC DESIGN AND ANALYSIS)

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Abstract: This paper presents a standard list of procedures for designing natural fish passage structures in urban streams. Before any design can commence, designers need to thoroughly investigate the target fish species and the hydrology of the study reach. Designs of riffle grade controls (RGCs) and flow constrictor/step pools (FC/SPs) start with topographic surveys, geomorphic assessments, and tailwater measurements. Results of the geomorphic assessment will determine which structure should be constructed: RGCs for sand/gravel bedded streams and FC/SPs for cobble/boulder bedded streams. Each structure type has a unique hydraulic modeling approach; however, stone sizing and channel bank stabilization procedures are standard. Construction management is of great importance because installing these structures is not routine and it is incumbent on the designer to ensure that the contractor complies with the spirit and the intent of the design.

Introduction

This paper is the second of a two-part document that presents the methods for achieving fish passage in urban streams through the design and construction of natural fish passage structures specifically riffle grade controls (RGCs) and flow constrictor/step pools (FC/SPs). Methods presented herein are the second phase of design and should be undertaken only after gathering fisheries and hydrologic information discussed in the companion paper entitled, "Natural Fish Passage Structures in Urban Streams, Part 1: Hydrologic and Resource Issues," (Hegberg 2001). Although step-wise procedures are presented, readers are cautioned that a thorough understanding of the limitations of these, or any hydraulic modeling exercise, is essential for successful designs. Readers should also understand that these techniques are applicable for natural fish passage designs in rural streams and leaping fish even though the authors are presenting them in the context of urban stream fish passage.

Designing fish passage structures will always require a degree of customization since all sites exhibit unique characteristics that pose design challenges. However, standard activities are necessary for every design and are summarized in Figure 1. As previously stated, identifying target species, collecting fisheries data, and performing hydrologic studies are addressed in companion paper, Hegberg et al. 2001. This paper will continue with conducting an abbreviated geomorphic assessment, selecting an appropriate structure, and explaining the hydraulic modeling procedures.

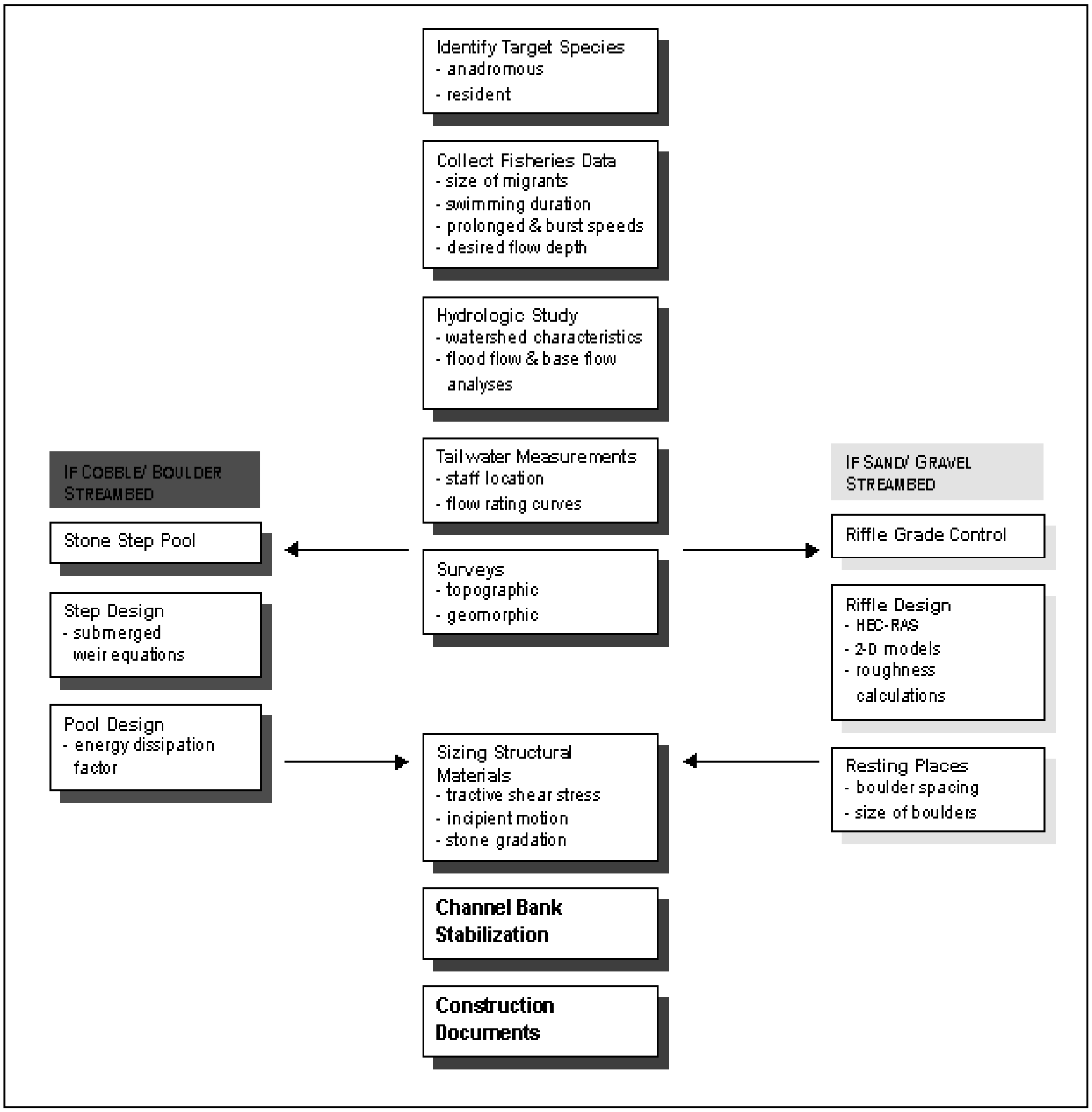


Fig. 1. Natural Fish Passage Design Flow Chart

Initial Design Activities

Topographic Surveys

Detailed topographic surveys involve locating and measuring elevations of floodplains, bank features and streambed features. Study boundaries commonly extend 1000 feet downstream and upstream of each blockage. From this surveying data, a digital terrain model (DTM) is created and can be blended with a DTM obtained locally from general aerial surveying. This combined DTM is used to create cross sections, stream profile and one-foot contour maps of existing conditions. Designers should avoid performing cross sections surveys instead of detailed topographic surveys because a significant amount of detail would be lost. Surveys are also used in floodplain modeling to assess the impacts of the proposed structures.

Geomorphic Surveys

Geomorphic surveys provide valuable information regarding dominant discharge, shear stresses, and the size of the sediment being transported and deposited in the study reach. Careful analysis of the sediment is important because the median particle size (D_{50}) will determine whether the RGC or the FC/SP will be used for fish passage. Geomorphic surveys would consist of pebble counts in the streambed and bar sampling of side, point, and mid-channel bars. Procedures for conducting these surveys may be found in Rosgen (1996). If the median particle size were sand or gravel, an RGC would likely be the structure of choice. FC/SPs would be the preferred structure if the median particle size were cobbles or boulders.

Tailwater Measurements

Tailwater measurements provide the basis for calculating the hydraulic drop, which governs the number of FC/SPs or the length of RGCs. These measurements replace hydraulic modeling for the baseflow condition, as traditional one-dimensional hydraulic models cannot be used to model baseflow. Baseflows are of shallow depths that are significantly effected by channel roughness; one dimensional models may not be sensitive enough to evaluate the required effects. Staff gages or automated transducers/data loggers should be installed downstream of the proposed structure and outside the influence of construction. Stream stages are read for flows ranging from baseflow to low storm flow. A minimum of three flow and stage measurements are required to produce a rating curve of stage versus discharge. If pressure transducers are used frequency analyses can be performed to estimate the dominant tailwater elevation.

Designing Natural Fish Passage Structures

Using the calculated design flows, the preliminary structure is designed using standard hydraulics equations. As part of this process, the following concerns must be thoroughly addressed (Acharya 2000):

- Cross section geometry
- Structures for resting places
- Size and shape of stone
- Profile slope
- Fishway hydraulics including flow division and resistance
- Structural stability

Later stages of design may involve the use of two-dimensional flow models such as FESWMS from the Federal Highway Administration and RMA/TABS from the U.S. Army Corps of Engineers -WES to evaluate key transition surfaces for stability and compliance with the design criteria.

Flow Constrictor/Step Pools

Hydraulic Design

FC/SPs are rock structures designed to concentrate flow to provide necessary water depth and velocity for traversing blockages (Figure 2). In their basic form, FC/SPs are linear structures with multiple rock weirs set at different elevations to provide fish passage for varying flows and stages. Multiple weir openings also provide redundancy to account for debris and the range of design flows. Multiple steps are installed in series with the gaps in these step horizontally offset to force lateral flow through the intermediate pools.

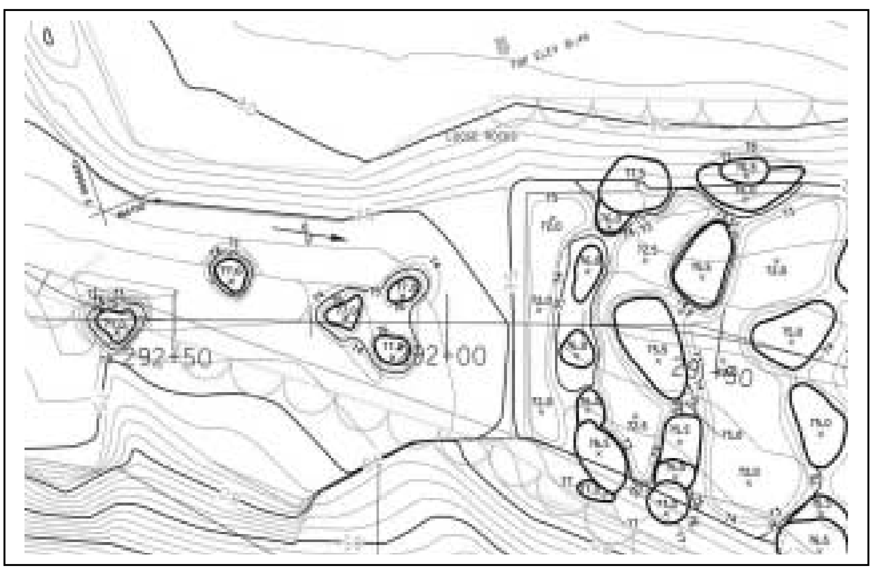


Fig. 2. Flow Constrictor/Step Pool Plan View

For FC/SP design, the hydraulic model for baseflow conditions must be based on rapidly varied flow equations. FC/SP design begins with determining the hydraulic drop between the headwater and tailwater elevations using the low end of the design flow range (i.e., 10-percentile non-exceedance) as the basis for the tailwater elevation. The hydraulic drop is then divided by 6 inches to obtain the number of steps for smooth transitions. A six-inch drop from step to step reduces the flow velocities and submerges the weirs, which provides streaming flow over these steps (Chow 1959). Smooth streaming flow step transitions are required for anadromous species since they are non-leaping, relatively weak swimmers.

This is illustrated in Figure 3. Figure 3 is a photograph of a known fish blockage in a tributary to the Susquehanna River with a hydraulic drop of 8 inches. During the migration season, American shad become trapped at this point and either turn back or die. For salmonids, this location would likely be traversable; however, the plunging flow prevents weaker alosids from moving up the tributary. This example illustrates the importance of understanding the capabilities of the target fish species and designing structures to strict criteria.

Fig. 3. Known Fish Blockage — Susquehanna River Tributary

Modeling FC/SPs is primarily a function of solving rapidly varied flow equations. A spreadsheet model of the entire structure is built to evaluate the widths of each weir opening and the height of each step. Figure 4 is an example of a spreadsheet solution to a single step in a FC/SP design that is based on Equations 1 and 2 (King 1976).

$$\frac{Q}{Q_1} = \left[1 - \left(\frac{H_2}{H_1}\right)^{1.5}\right]^{0.385} \qquad \text{Villemonte Submerged Weir} \qquad (1)$$

$$Q_1 = CL_W H_1^{1.5} \qquad \text{Weir Equation (m}^3\text{/s)} \qquad (2)$$

Frequency:	9%					
TARGET Q:	30.0	must match		input		
Tail Water elevation:	149	149	149	149	149	
STATION 410+11						
	A	B	C	D	E	54.0
Weir elevation	148.35	148.85	149.35	149.85	150.35	Length Total
Weir length	6.0	6.0	16.0	26.0	0.0	54.00
C coefficient	3.1	2.8	2.2	2.0	2.0	
Tail Water (H2)	0.65	0.15	-0.35	-0.85	-1.35	
Head Water (H1)	1.17	0.67	0.17	-0.33	-0.83	guess
H2 / H1	0.556	0.224	-2.059	2.576	1.627	
Q / Q1	0.814	0.958	1.000	1.000	1.000	
Q1	23.54	9.21	2.47	0.00	0.00	Q Total
Q	19.16	8.82	2.47	0.00	0.00	30.45

Fig. 4. Example Weir Equation Spreadsheet

In the above equations, L_w is the effective length of the weir crest (width of the weir flow opening); H_1 is the upstream head on the weir (measured above the crest elevation); H_2 is the downstream tailwater head (measured above the crest elevation); Q_1 is the unrestricted flow over the weir (with no tailwater); and Q is the adjusted flow over the weir due to tailwater conditions. The value of C should be calibrated based on field measurements of similar structures.

Spreadsheet calculations presented in Figure 4 represent an iterative process for only one design flow. Weir openings are optimized to provide the design fish passage velocity through at least one opening for all of the design flows. In this case, the FC/SP spreadsheet contains five weirs, the two highest weirs representing cumulative crest lengths. The three lowest weir openings are positioned along this crest to provide fish passage at different flow stages. Weir A would operate at the lowest stages. As flow and stage increase, fish would begin to pass through weirs B and C. Weirs D and E are step crest elevations that represent a flow separation at the highest baseflow stages or low storm flows. This flow separation in a national park setting is necessary for the aesthetics of a natural looking fishway. High storm flows would pass over the FC/SP structure and into the floodplain.

Pool design is based on the Energy Dissipation Factor (EDF) (Equation 3) (Washington Department of Fish & Wildlife 1999) and is generally limited by the 90-percentile flow.

$$EDF = \gamma \frac{QD_S}{V_P}$$ Energy Dissipation Factor (Pa/s) (3)

The EDF is a measure of turbulence and the resulting bubble formation. EDF values greater than 4 lb/ft^{2}s indicate that flow in a pool is turbulent enough to disorient and fatigue individual fish. In the above equation, Q is the flow through individual openings; D_s is the hydraulic drop of the step (H_2-H_1); V_p is the volume of the pool; and γ is the unit weight of water.

Pool volume greatly impacts EDF; however there are limitations on sizing pools. Pool length (for the calculation only) is limited to less than 10 ft; the average width of the pool (for the calculation only) is limited by a 4:1 side expansion from the weir opening; and the depth should be at least 3 D_s and sufficiently deep to submerge any hydraulic jump (Chow 1959).

Measuring Existing Boulder Clusters

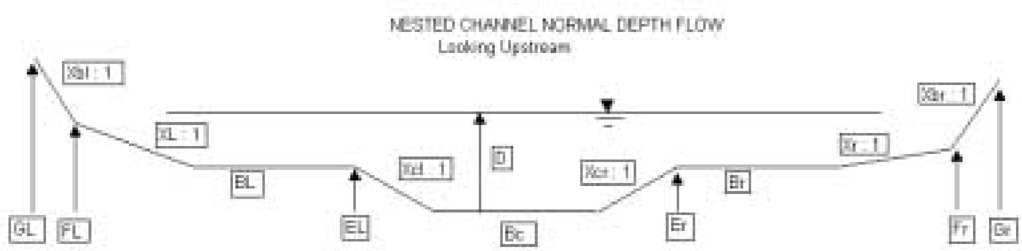
FC/SPs mimic boulder clusters in streams because the type of flow through both structures is similar. Therefore, designers would find it useful to examine boulder clusters in the subject stream or similar streams to attain a deeper understanding of the flow regimes the constructed structures are to mimic. Designers should measure the lengths and flow depths in natural weirs, velocities through the weirs, the lengths and depths of natural pools, and locations of rocks to develop a "map" of the boulder cluster. Information obtained from such a survey can be used to calibrate the designed FC/SPs. Calibration is not intended to strictly measure the adequacy of the design, but is to give the designer qualitative indication of whether the structure will pass fish.

The authors have performed such boulder cluster investigations for the Woodrow Wilson Bridge Project, the results of which are discussed below. Relevant physical data was gathered at reference reaches along Rock Creek known as the 'Boulder Field' to understand naturally occurring velocities, discharges, and EDFs were evaluated. This evaluation process consisted of recording velocity profiles at naturally occurring step pools, a bathymetric survey of pools, identification of channel and bar configurations for high flows events, documenting cross section and longitudinal profiles and photographic documentation. Discharge during field visits ranged from 19 to 25cfs. From this field data energy dissipation factors were calculated for each step pool feature. Velocities in natural weir pools on Rock Creek ranged from 0.05 to 4.7fps, and Energy Dissipation Factors ranged from 1.3 to 11.5lb/ft^2 s.

Riffle Grade Controls

Hydraulic Design

Riffle Grade Controls (RGCs) are rock structures that mimic riffle sections of streams and are designed to stabilize streambeds (Figure 5). RGCs are constructed in four sections: an upstream glide section, a crest transition, a long riffle section, and a downstream run section. Glide sections transition flow from an upstream pool to the crest. The crest is provided to reduce stresses on the upstream end of the riffle. Riffle sections are designed to pass sediment and fish while providing channel stability. Runs are transitions into a downstream pool or an existing run and are designed to prevent scour hole formation.



BL	0
EL	1
FL	2
GL	3
nL	0.06
XL	20
Xbl	2

Bc	6
Dstart	0.5
Xcl	2
Xcr	2
Rock (ft)	1
n	0.06
So	0.016

Br	0
Er	1
Fr	2
Gr	4
nr	0.06
Xr	20
Xbr	2

DESIGN FLOWS

		Left Side		Pilot Channel		Right Side	
Occurance	Q(cfs)	d(ft)	V (fps)	d(ft)	V (fps)	d(ft)	V (fps)
9%	20			1.00	2.62		
50%	40	0.35	0.98	1.35	3.33	0.35	0.98
90%	150	1.15	2.33	2.15	4.74	1.15	2.33

Fig. 5. Example Manning's Equation Spreadsheet

Where baseflows are low, RGCs should be constructed with an armored nested channel to concentrate baseflows for improved depth. This nested channel would pass some light storm flows, while larger storm flows would spread onto a stone or vegetated bench area. Dividing flow in this manner allows coarser sediments to pass down the nested channel, while some fines are deposited on the adjacent bench.

Initial hydraulic baseflow design consists of spreadsheet solutions to Manning's equation for flow (Equation 4) (King 1986). Figure 6 presents an example of a spreadsheet used for the initial design.

$$Q = \frac{R^{2/3}S^{1/2}A}{n} \qquad \text{Manning's Equation } (m^3/s) \qquad (4)$$

Where R is the hydraulic radius; S is the bed slope (uniform flow assumed); A is the cross section area; and n is assumed from an estimate of bed stone sizes.

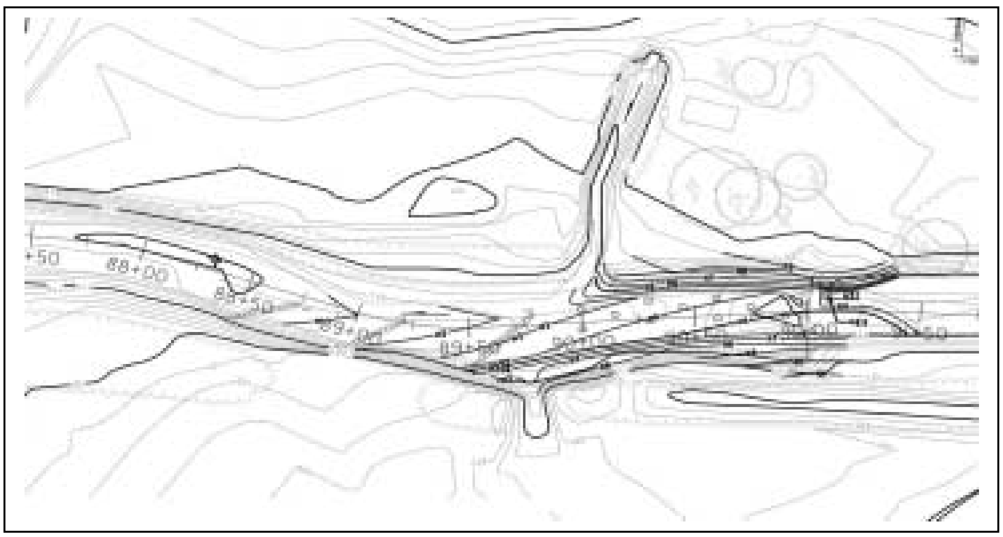


Fig. 6. Preliminary RGC Plan View and Cross Section

This spreadsheet operates by entering the dimensions of the RGC cross section into the spreadsheet. The user must also enter estimates of slope and Manning's n values for the nested channel and the overbank areas. Manning's equation is solved on a back end spreadsheet (not shown) for various flow depths for the nested channel and the overbank areas separately. RGC slope, cross section, and Manning's n values are adjusted until the desired depth and velocity are found.

Gradually Varied Flow Modeling

As the modeling process continues, more detailed hydraulic modeling for baseflow, top of bank and flood conditions should be performed using gradually varied flow equations. One-dimensional (1-D) models, such as HEC-RAS can be used. In general, a HEC-RAS model is created for a long reach to identify flood stages and the water surface for dominant discharge or top-of-bank events. HEC-RAS is limited because these models are based on average cross section conditions, rendering it susceptible to missing local flow variations that may occur at certain locations along the RGC especially at transition points.

To address limitations in 1-D modeling, two-dimensional (2-D) modeling should be performed. These models are useful for identifying areas of excessive shear stress and areas that may not meet the hydraulic design criteria. Finite Element Surface Water Modeling System (FESWMS) is a common 2-D model that is available from the Federal Highway Administration or is a module in commercial surface water modeling programs. This software is useful because the models can be tailored to the site-specific conditions by manipulating elements within computer representations of the proposed structures. Calibration of the model may be desirable and requires modification of the input parameters to a numerical model until the output from the model matches known observed data. Unlike conventional 1-D flow analysis, outputs include flow velocities, flow depths and shear stress on a 2-D plane parallel to the water surface (Figure 7). This type of information allows confident designs ensuring that fish passage requirements are met.

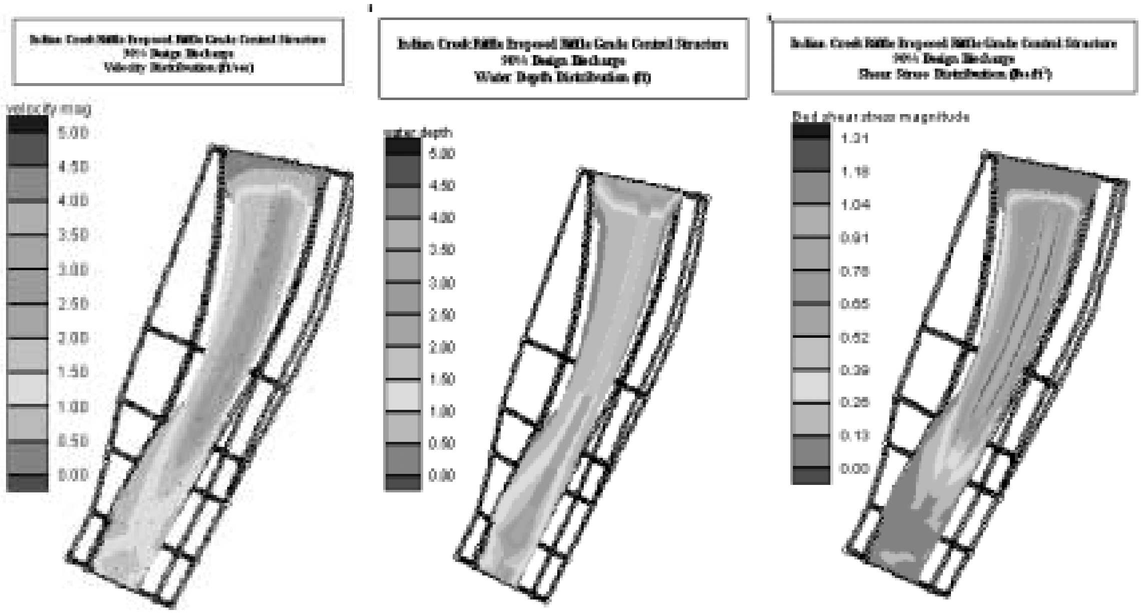


Fig. 7. 2-D Model Output for RGC—Depth Valocity and Shear Stress

A major concern in hydraulic modeling is defining roughness in RGC designs. For top of bank and flood flow conditions, standard methods of determining Manning's n can be used. At these deeper flow depths, roughness is primarily based on the channel geometry and general surface materials. However at baseflow levels, the flow is so shallow that the roughness can be based on flow around and over individual rock. This relative roughness condition requires different methods of predicting and using Manning's n.

As a final step in boulder selection, the initial assumptions concerning roughness are verified. The Manning's n value used in the hydraulic models is estimated using equations developed from relative roughness and natural stream studies. Relative roughness is classified into small-scale, intermediate-scale, and large-scale roughness based on relative submergence as follows: (Bathurst 1978, Shea 2000).

Small-Scale Roughness	Intermediate-Scale Roughness	Large-Scale Roughness
$\frac{d}{D_{50}} > 7.5$	$7.5 > \frac{d}{D_{50}} > 2$	$2 > \frac{d}{D_{50}}$
$\frac{d}{D_{84}} > 4$	$4 > \frac{d}{D_{84}} > 1.2$	$1.2 > \frac{d}{D_{84}}$

Where d is the flow depth; D_{50} is the median particle size; and D_{84} is the 84-percent size of the median axis length.

Since the design flow depths are shallow during migration periods, the large-scale roughness criteria generally applies. A regression-fitted relationship was developed based on measurements of flow in mountain streams composed of boulders and cobbles where the relative submergence in the data ranged between 0.2 and 4 (Mussetter 1989). This relationship is:

$$\sqrt{\frac{8}{f}} = 1.11\left(\frac{d}{D_{84}}\right)^{0.46}\left(\frac{D_{84}}{D_{50}}\right)^{-0.85} S^{-0.39} \quad (5)$$

Where S is the friction slope; and *f* is the Darcy-Weisbach friction factor. The Darcy-Weisbach friction factor can be related to Manning's n by:

$$n = \frac{R^{1/6}}{\sqrt{g}\sqrt{\frac{8}{f}}} \quad (6)$$

Where R is the hydraulic radius and g is the gravitational acceleration.

For small-scale roughness, the Manning's n is estimated using traditional methods. In the hydraulic models, Manning's n can vary with depth. The roughness values for corresponding depths are compared to the original roughness assumptions. If significant differences are found, the hydraulic models are adjusted, rerun, and the shear stresses are reevaluated. Because of site-specific hydraulic issues due to bridges, levees or channel types, each riffle grade control has the potential for needing a unique design. However after evaluating the extremes in site geometry and flow conditions, generalizations and interpolations in between these extremes can be made based on the results of a HEC-RAS model.

Results of 2-D modeling may show that several areas of higher shear stresses localized on the initially proposed channel geometry. For example, a high flow stress zone may be identified at the crest of the RGCs, which has been identified by others (Ayers 1998, Thorncraft 1996, Wildman 2001). To solve this particular problem, a class of stone could be used to compensate for these higher flow stresses. The 2-D model may also indicate that the edges of any nested channel feature will receive high flow stresses. Larger stone and robust vegetative cover could be used to stabilize these areas.

Resting Places

As previously stated, fish exhibit varying degrees of swimming abilities and those of the weakest fish must be accounted for in natural fish passage designs. This is especially true for RGCs since these structures tend to be relatively long, posing potential endurance barrier problems. Therefore, fisheries documents from research (Katopodis 1994) and agencies such as the U.S. Fish and Wildlife Service and state natural resource agencies should be consulted to determine the need for and the appropriate distance between resting places. The spacing of the boulders within a particular boulder garden is based on recent flume studies (Acharya 2000). From their recommendations, spacing of boulders within a garden or cluster is 4D cross channel and 6D longitudinally is chosen, where D is the size of the exposed boulder.

Sizing Structural Materials

The selection of the stone for use in constructing natural fish passage structures is based on a standard channel design method. Stone for RGCs should be well graded to provide for better compaction and a degree of impermeability that will prevent low flows from flowing through the structure instead of over it. Boulders for FC/SPs should be large enough to remain stationary during flood flows and should be well sorted.

The tractive force, or tractive shear stress, method is utilized to determine from calculations or graphs this size particle that corresponds to a particular shear stress that represents the flood stage of highest impact on the structure. Care should be taken when selecting the material sizes because these structures cannot be allowed to mobilize during flood (Johnson 1999). The selection process is iterative and based on assumptions of stone size and roughness, which must be verified and refined with hydraulic modeling.

Proposed RGCs were modeled using HEC-RAS and the 2-D hydraulic software to determine the tractive shear stresses on the fishway. The 2-D model considered 9-, 50- & 90-percent of base flow and the top of bank flow conditions. The actual shear stress values were compared to the upper limit of incipient motion from field and laboratory studies (Leopold 1964). For comparison, a computation of stone size was performed from critical shear stress methods. Conservative values were chosen for a computation of dimensionless critical shear stress from cobble - gravel river studies (Equation 7) (Andrews 1983). Then the incipient stone size was computed from equation 8 (Shields 1936). Additionally, the coefficient of curvature ($C_z = D_{30}^2/(D_{60} * D_{10})$) should range between 1 and 3, suggesting a well-graded material (Craig 1993). Based on this criterion, the stone for the riffle grade control structures were sized.

$$\tau_{ci}^* = 0.0834\left(\frac{d_i}{d_{50}}\right)^{-0.872}$$ Dimensionless Critical Shear Stress (7)

$$\tau_{ci} = \tau_{ci}^*(\rho_s - \rho)g d_i$$ Critical Shear Stress (8)

Where ρ is the density of water; ρ_s is the density of the rock; g is gravity; d_{50} is the median rock size; d_i is the size of the stone for incipient motion.

The sizes of stone used for boulder clusters, boulder gardens, and steps are based on field studies of existing, exposed grade control structures, and include foundation boulders (Rosgen 2001). The advantage of using field studies for boulder sizing is that these studies inherently include the effects of such hazards as debris and ice impact.

Channel Bank Stabilization

Construction of a FC/SP or RGC will likely alter shear stresses on the banks in the vicinity of the structures. In the course of designing these structures, attention should be paid to the changing forces affecting bank stability, and stabilization should be conceived as part of the construction process. Sizing of the stone for bank stabilization can be made using typical bank stability guidelines. If an RGC has a bench, like the natural channel, this bench should be planted using a robust method like brush layering.

Construction Issues

Natural fish passage designs must be followed up with careful construction. Stream flow is very sensitive to changes in slope and cross section; therefore, tight tolerances should be incorporated into every construction contract. The authors have witnessed RGC construction projects where the slope, cross section, and material sizes were incorrectly installed resulting in severe structure scour.

Examples of tolerances are as follows: for RGCs 1) Slope: ± 0.1 percent, 2) Cross Section: ± 2 feet, 3) Elevation: ± 0.2 feet. For FC/SPs, example tolerances are as follows: 1) Elevation: ± 0.2 feet and 2) Weir Width: ± 1 foot.

It is always recommended, as part of the design, that models of proposed structures be manipulated to study the sensitivities of the designs. Since the authors are working with relatively weak fish, slight changes to structure design could have a significant impact. Structures designed to pass salmonids, for example, may be less sensitive to such changes. Tolerances are an extremely important part of these designs and should be thoroughly understood. In addition, field studies of the flow characteristics should be conducted during and after construction of these fishways. The hydraulics of these structures should be verified and computer models calibrated to field conditions during the monitoring phase.

It is also recommended that designers manage the construction of the design to ensure that contractors install them correctly. For example, designers can collect field measurements during construction of FC/SPs to ensure that the flow conditions of the installed structure meet the design criteria. Additionally, elevation data can be collected during the installation of RGCs to ensure the structures are constructed with the proper slopes. Installing these structures is not routine, and a lack of conscientious monitoring could cause problems later.

Conclusion

Design procedures expressed in this paper are based on the present knowledge base. However, procedures will evolve as more of these structures are installed. The authors will be collecting data on RGCs and FC/SPs being installed in the Washington, D.C. metropolitan area in the summer of 2002, all of which were designed for point-blockage fish passage and not total stream restoration.

Acknowledgements: The authors would like to acknowledge Conor Shea of the Potomac Crossing Consultants; Christopher Heyn and Joshua G. Gilman of KCI Technologies, Inc.; Kevin Kelly of Environmental Systems Analysis, Inc.; and Dick Quinn of USF&WS Northeast Region for contributing valuable information to this document.

References

Acharya, M., J.A. Kells, & C. Katopodis. 2000. “Some Hydraulic Design Aspects of Nature-like Fishways,” Proceedings of the Joint Conference on Water Resources Engineering and Water Resources Planning & Management, ASCE, Reston, VA.

Andrews, E.D. 1983. “Entrainment of Gravel from Natural Sorted Riverbed Material,” Geologic Society of America Bulletin 94, p. 1225-1231.

Ayres Associates. 1998. Two-dimensional Modeling of a Natural Riffle and Gradient Restoration Facility, Riverbed Gradient Restoration Structure Glenn-Colusa Irrigation District (GCID) Intake, prepared for the Army Corps of Engineers, Sacramento District, Contract No. DACW05-90-C-0168.

Bathurst, J.C. 1978. “Flow-resistance of Large-Scale Roughness,” Journal of the Hydraulics Division, ASCE, Vol. 114, No HY12, p. 1587-1603.

Center for Watershed Protection. 2000. *Urban Stream Restoration Practices: An Initial Assessment*, October 2000.

Chesapeake Bay Program. 2000. Chesapeake Bay Program Website, www.chesapeakebay.net.

Chow, V.T. 1959. *Open Channel Hydraulics*, McGraw-Hill, NY, NY.

Craig, R.F. 1993. *Soil Mechanics*, Chapman & Hall, London.

ESA. 2000. *Monitoring of Existing Fish Passage Structures*, Environmental Systems Analysis, Inc., August 2000.

Hegberg, C.H., S. Jacobs, P.A. Schlindwein, & S.J. Cohen. 2001. “Fish Passage in Urban Streams Part 1: Hydrologic and Resource Issues,” this proceeding.

Hogan, S.A., M.R. Peterson, T.W. Smith & P. Valentine. 2000. “Sacramento River Gradient Restoration Facility,” ASCE 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management.

Johnson, P. A. 1999. “Comparison of Traditional Engineering Approaches to Natural Channel Design,” Proceedings North Carolina Stream Restoration and Protection Conference, NC State University, Asheville, NC, p. 45-47.

Katopodis, C., *Introduction to Fishway Design*, Freshwater Institute, Department of Fisheries and Oceans, Manitoba, Canada, 1992.

Katopodis, C. 1994. “Analysis of Ichthyomechanical Data for Fish Passage or Exclusion System Design,” Proceedings of an International Fish Physiology Symposium, Vancouver, Canada, Fisheries Society and Fish Physiology Association, p. 318-323.

KCI. 1996. *Conceptual Report*, *White Marsh Run (Main Stem) Stream Restoration*, KCI Technologies, Inc., November 1996.

King, H.C. & E.F. Brater, 1976, *Handbook of Hydraulics*, McGraw-Hill, NY, NY.

Leopold, L.B., M.G. Wolman & J.P. Miller, 1964. *Fluvial Processes in Geomorphology*, Freeman, San Francisco, CA.

Maidment, D.R., 1993. *Handbook of Hydrology*, McGraw-Hill, Inc.

Maryland Department of Natural Resources, Verbal Communication During an Inspection of Riffle Grade Control Structures, White Marsh Main Stem, White Marsh, Maryland, March 2000.

Maryland Office of Planning, 1998. *Maryland Property View - Montgomery County*, Baltimore MD.

McCuen, R.H. 1998. *Hydrologic Analysis and Design*, Prentice Hall, Saddle River, N.J.

Mussetter, R.A.. 1989. *Dynamics of Mountain Streams,* Ph.D. Dissertation, Dept. of Civil Engineering, Colorado State University, Ft. Collins, CO.

Newbury, R.W. & M.N. Gadoury. 1993. *Stream Analysis and Fish Habitat Design*, Newbury Hydraulics, Ltd., Gibsons, British Columbia.

Rosgen, D. 1996. *Applied River Morphology*, Wildland Hydrology, Pagosa Springs, CO.

Rosgen, D. 2001. River Restoration & Natural Channel Design class handouts – excerpts from a draft paper, Wildland Hydrology, Pagosa Springs, CO.

SES. 1999. *Stormwater Management Plan Update*, Baltimore/Washington International Airport, Straughan Environmental Services, Inc., May 1999.

Shea, C. 2000. Project Correspondence, Parsons Brinkerhoff, Baltimore, MD.

Shields, A. 1936. "Application of Similarity Principles and Turbulence Research to Bedload Movement".

Sloto, R. & A. Crouse. 1996. "M.Y., HYSEP: A Computer Program for Streamflow Hydrograph Separation & Analysis," US Geological Survey, Water Resources Investigations Report 96-4040.

Translated by W.P. Ott & J.C. Uchelen, California Institute of Technology, Pasadena, CA, Report 167.

Thorncraft, G.A., & J. Harris. 1996. *Assessment of Rock Ramp Fishways*, NWS Fisheries Research Institute and the Cooperative Research Center for Freshwater Ecology.

Valentine, P. & C. Rairden. 2000. Personal Correspondence, USACOE, Sacramento, CA.

Washington Department of Fish and Wildlife. 1999. *Fish Passage Design at Road Culverts, A Design Manual for Fish Passage at Road Crossings*, March 3, 1999.