

A Design Procedure for Sizing Step-Pool Structures

D.B. Thomas (1), S.R. Abt (2), R.A. Mussetter (1), M.D. Harvey (1)

(1) Mussetter Engineering, Inc. 1730 S. College Avenue, Suite 100, Fort Collins, Colorado 80525 (970) 224-4612; FAX (970) 472-6062; email: dai@mussei.com

(2) Hydraulic Engineering Laboratory, Colorado State University, Fort Collins, Colorado 80523 (970) 491-8203 email: abt@lance.colostate.edu

Abstract

Step-pool structures (vortex weirs) are being used to provide (1) vertical stabilization during high flow, and (2) low-flow instream habitat in restoration of disturbed low-gradient streams. A study of eight steep, coarse-grained mountain streams in Colorado identified the geomorphic and hydraulic characteristics of natural step-pool structures and was used to develop a design procedure for sizing and spacing step-pool structures.

Regression equations were developed for determining the pool length, scour depth, maximum pool width, and the amount of contraction required to provide downstream tailwater control. Independent variables included step height, channel slope, 25-year unit discharge, and active channel width. Other requirements identified included confinement of flow over the weir, a low-flow notch, sizing and interlocking of the boulders comprising the step, adequate tailwater control and bank protection in the downstream pool. The sizing and arrangement of the particles comprising the step centers around a few key particles termed anchor boulders that are the largest size class found within the channel, and are on the order of 1 m in diameter. They provide stability to the weir and confinement of flow over the weir. Boulder size is not controlled by the channel hydraulics, but rather by availability and lithology.

Introduction

Features that purport to represent step-pool structures (e.g. vortex weirs) are being widely used to provide vertical stability in channel restoration projects and habitat enhancement in severely perturbed streams. However, the use of such structures in geomorphic settings that have very different characteristics than those where they are found naturally, results in a high degree of failure exceeding 50 percent over 10 to 20 years (Morris, 1995). In many cases, failures have resulted from insufficient understanding of the genesis of step-pool structures. Reasons for these failures are numerous, but the principal reasons include the absence of design criteria for locating and sizing the structures.

The objectives of this paper were to identify the factors that influence the performance of natural and man-made step-pool structures, and to present a procedure for integrating step-pool structures as functioning, low-drop grade-control structures, and habitat enhancement features.

Step-pool channels are characterized by an accumulation of cobbles and boulders into organized discrete transverse ribs spanning the channel (Montgomery and Buffington, 1997). The ribs form an alternating series of steps and pools resulting in a stepped, longitudinal stream profile. Step-pool structures are characteristic of relatively steep, coarse-grained (boulders), and confined mountain streams; they provide both grade control during high flows and instream habitat during low flows (Meehan and Bjornn, 1991).

Step-pools are found in a wide range of environments ($S_o > 0.04$), including humid streams (O'Loughlin, 1969; Hayward, 1978,1980; Newson and Harrison, 1978), arid desert fluvial systems (Clarke and Hansen, 1988), and in areas formerly affected by glacial processes (Newson and Harrison, 1978).

The alternating sequence of supercritical flow over the steps and subcritical flow in the pools provides the ability to overcome steep slopes by energy dissipation (Heede, 1972,1981) mainly through the formation of roller eddies (Hayward, 1978,1980). Under low-flow conditions, each step may be considered as a low-drop, grade-control structure (Abt et al., 1990), with a difference in elevation (H) between the up- and downstream channel beds, at a discharge (Q), and a corresponding critical depth (y_c), such that the relative drop height, H/y_c , is equal to or less than 1.

Step-pool formation requires (1) near-critical to supercritical flow conditions over the bed and must be close to, but not exceed, the entrainment threshold for the larger particles (D_{90} or larger) (Grant and Mizuyama, 1992), and (2) high discharges and low sediment supply (Ashida et al., 1981; Grant et al., 1990).

Spacing between steps is typically one to four channel widths (Chin, 1989); the spacing decreases with increasing channel slope (Grant et al., 1990) and corresponds to maximum flow resistance (Whittaker and Jaeggi, 1982). The spacing of natural step-pools can be approximated by

$$L = \frac{0.3113}{J^{1.188}} \quad (1)$$

where L is the average step length (m), and J is the channel slope.

Paleohydraulic reconstruction (Grant et al., 1990) indicates that the large bed-forming material is mobilized during hydrologic events with recurrence intervals on the order of 20 to 50 years. The step-pools are reformed on the falling limb of the hydrograph (Whittaker, 1987a,b).

The maximum channel velocity and associated boundary shear stresses occur when pools have completely filled with sediment. The transport capacity of the channel increases with pool-filling, thus, providing negative feedback inhibiting significant sediment storage (Whittaker and Davies, 1982), allowing an increased sediment load to be rapidly transported downstream (Montgomery and Buffington, 1993).

Salmonids prefer habitat that provides resting areas where the current is slow, there is an adequate food supply, and provides cover from predators. Table 1 summarizes preferred pool habitat preferences for trout. Adult trout can negotiate single vertical jumps of 0.3 to 0.45 m (1 to 1.5 ft) (USDOT, 1979). Wydoski and Duff (1982) suggest the height between the up- and downstream water surface should not exceed 0.45 to 0.61 m (1.3 to 2 ft).

Table 1. Summary of Physical Habitat Preferences for Trout.			
Author	Function	Pool Depth	Pool Velocity
Thompson (1972)	Passage	> 0.12m	< 1.22 m/s
Thompson (1972)	Spawning	0.12 to 0.18 m	0.30 to 0.91 m/s
Wesche (1973)	Habitat	> 0.15 m	
Lewis (1969)	Habitat	>0.46 m	<0.30 m/s

Physical Settings

Seven step-pool channels located in Colorado's Arkansas River Basin were selected for analysis: Browns, Halfmoon, Hayden, Horn, Little Cochetopa, Middle Fork Cottonwood, Newlin and North Fork Lake Creeks (Figure 1). Two additional step-pool study sites were selected on the Roaring River in Rocky Mountain National Park (RMNP) for a detailed stability analysis of the particles comprising the steps, as well as the hydraulic and geomorphic properties of the step-pool structures. The hydraulic, geomorphic, and habitat characteristics of four man-made step-pool structures located in the San Miguel River, within the town of Telluride, Colorado, were also determined for comparison with natural step-pool channels.

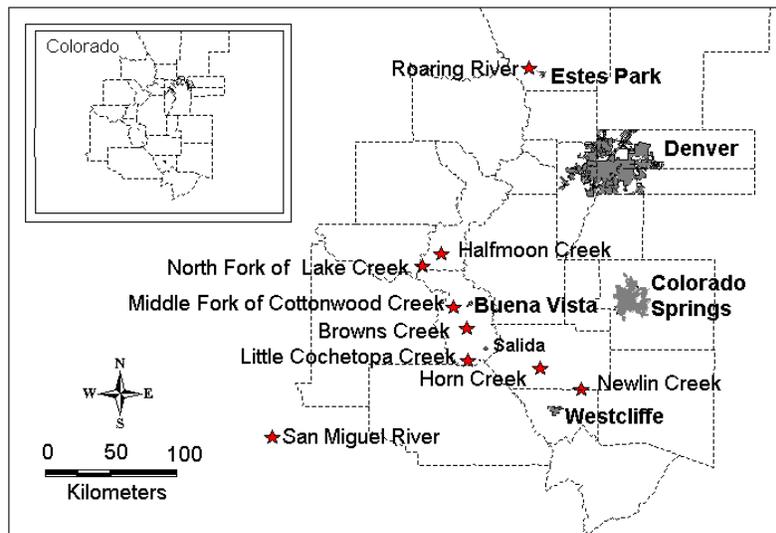


Figure 1. Step-pool study site locations.

The natural step-pool study reaches are located in coarse-grained, steep mountain channels. The channel gradients at the selected sites (Arkansas River and Roaring River sites) vary from 0.015 to 0.081, with a mean of 0.053, which is consistent with the published slope values (Whittaker, 1987; Chin, 1989; Grant et al., 1990). The drainage basins at the study sites (Table 2) are relatively small with a mean drainage basin area of 35.1 km², and they are located at high elevations with a mean drainage basin elevation of 3,450 m. The channel bed material and boulders comprising the steps are formed of very competent granite, metamorphic, and meta-sedimentary rocks.

Distribution of the step-pool structures is influenced by the processes that deliver coarse sediment to the channel and create the confinement of flow necessary for step-pool formation. The sites on Halfmoon, Horn, Little Cochetopa, and North Fork Lake Creeks are influenced by former glacial processes. They typically consist of very coarse, boulder channels set within confined, nonerodible banks. Middle Fork Cottonwood Creek has incised into a coarse cobble/boulder terrace fill and an alluvial fan located on the true left bank causes significant channel constriction. The Browns Creek and Newlin Creeks sites are set within debris flow deposits, and the Roaring River sites are set within very coarse-grained, flood and debris flow deposits resulting from an upstream dam failure (Jarret and Costa, 1986).

Site	Drainage Area km ²	Channel Slope (m/m)	D ₅₀ Bed- material (mm)	Mean Size of Boulders Comprising the Step (mm)
Browns Creek	27.2	0.0811	45	500
Halfmoon Creek	60.7	0.0150	60	450
Horn Creek	11.3	0.0774	48	520
Little Cochetopa Creek	17.0	0.0698	72	560
Middle Fork Cottonwood Creek	67.6	0.0476	65	490
Newlin Creek	26.7	0.0760	49	660
North Fork Lake Creek	36.6	0.0350	55	540
Roaring River, RR-1	29.7	0.0540	39	690
Roaring River, RR-2	29.7	0.0292	48	630
San Miguel River	66.4	0.0058	52	890

Four step-pool structures (rock weirs) were installed in 1989 in a channelized reach of the San Miguel River for habitat enhancement purposes. Since that time, the structures have withstood several large flows without significant damage. Bed material consists of relatively uniform gravel-sized materials ($D_{50}=52\text{mm}$), which are more mobile than those found in natural step-pool channels. Channel slope is an order of magnitude flatter than where natural step-pool structures exist. A similar distribution of boulders exists at all the man-made structures, with median boulder size for all steps being approximately 1 m in both the parallel and perpendicular directions to flow.

Data collected at the selected sites included sediment samples, assessment of geomorphic characteristics of the study reaches and step-pool structures, and topographic surveys of the study reach, including channel cross section, water-surface profiles, and longitudinal thalweg profiles. Topographic survey data were used to develop one-dimensional hydraulic models (HEC-2 COE, 1991; HEC-RAS COE 1997) of the sites. Results from the hydraulic models and field data were used in a statistical analysis to identify significant step-pool geometric and hydraulic parameters.

Results

Field observations revealed several features common to most of the boulder-step structures. These features include the shape of the weir crest, arrangement and sizing of the boulders comprising the weir, and contraction-induced tailwater control for the pool (Figure 2)(Table 3). These features influence the hydraulic function of the structure and its habitat value.

The weir of the step-pool structure is generally composed of a few very large boulders that play a key role in the stability and function of the step. The “anchor” boulders are usually located at the ends of the weir, and/or may be dispersed along the weir. Anchor boulders are typically the largest size class found within the channel and are on the order of 1 m in diameter, providing stability to the weir and confinement of flow over the weir. Boulders are commonly arranged in a broad v-shape, with the apex of the weir pointing upstream. The curvature of the weir tends to align the flow towards the center of the downstream pool. This has two important effects: (1) alignment of flow into the downstream pool helps maintain the downstream scour hole, and (2) it prevents flow from being directed towards the outer banks, and therefore, limits bank erosion. Other boulders comprising the weir interlock with the more stable anchor boulders.

The number of anchor boulders per weir varied from 1 to 10, with an average of 4. Although no strong relation was found between the number of anchor boulders comprising the step and the channel width, the data indicate that wider channels have a greater number of anchor boulders per step. All study sites had at least 2 anchor boulders per structure. At channel widths greater than approximately 6 m, the minimum number of anchor boulders per structure is typically between 4 and 6.

No relationships were identified for sizing the boulders comprising the step structures, indicating that the size of boulders comprising the weir is determined more by the available boulder size than by channel hydraulics. The average A-axis dimension of all the boulders was 640 mm, and the average B-axis dimension was 540 mm.

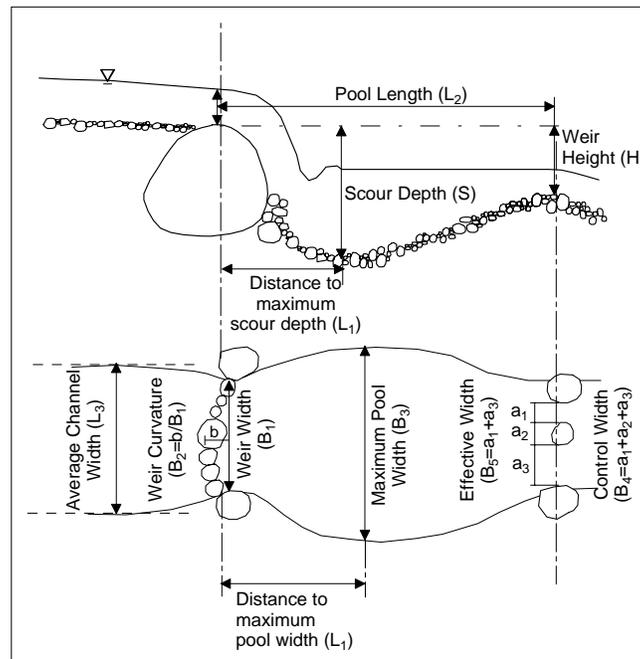


Figure 2. Details of the measured dimensions of the step-pool unit.

To determine the size of boulders for construction of man-made step-pool structures, the U.S. Army Corps of Engineers “steep slope riprap design” method was employed (COE, 1991). A D_{30} riprap size was computed using slopes of 2-, 5-, 7.5-, and 10-percent, and a unit discharge range from 0 to 4 m^2/s (Figure 3). Unit discharge was multiplied by a concentration factor of 1.25 as outlined in the COE (1991) procedures. The data indicate that the minimum boulder sizes found in natural step-pool channels are in the same size range as specified by the riprap design procedure, but the mean natural step boulder size is significantly larger than the computed D_{30} size. It appears, therefore, that the COE riprap-sizing procedure can be used to compute the minimum rock sizes for constructed step-pool structures, but these should be supplemented with anchor boulders. It is recommended that anchor boulders be placed along the step-pool structure to provide additional support and stability.

Table 3. Summary of average dimensions of the step-pool structures.									
Site Location	Step-Pool Dimensions (m)								
	Weir Width (B_1)	Weir Curvature (B_2)	Maximum Pool Width (B_3)	Width at Downstream Control (B_4)	Effective Width at Downstream Control (B_5)	Weir Height (H)	Scour Depth (S)	Pool Length (L_2)	Average Channel Width (L_3)
Browns Creek	3.1	0.0	4.0	3.5	3.1	0.2	0.3	3.9	3.5
Halfmoon Creek	6.9	0.1	6.1	4.8	4.8	0.6	0.5	7.0	8.8
Horn Creek	1.9	0.1	3.7	2.0	1.8	0.4	0.6	4.3	3.4
Little Cochetopa Creek	1.6	0.1	4.3	1.8	3.7	0.2	0.3	4.0	4.0
Middle Fork Cottonwood Creek	5.7	0.0	7.0	6.0	4.5	0.3	0.4	5.4	7.5
Newlin Creek	1.5	0.1	3.0	2.2	2.0	0.4	0.7	4.7	2.6
North Fork Lake Creek	7.0	0.1	8.0	7.7	5.9	0.2	0.3	5.3	8.9
Roaring River (RR-1)	4.6	0.0	5.8	6.4	5.3	0.2	0.5	6.6	4.6
Roaring River (RR-2)	6.4	0.0	6.4	4.3	4.3	0.1	0.3	3.1	4.6
San Miguel River	6.0	5.4	10.0	9.3	4.7	0.6	3.3	7.8	9.8

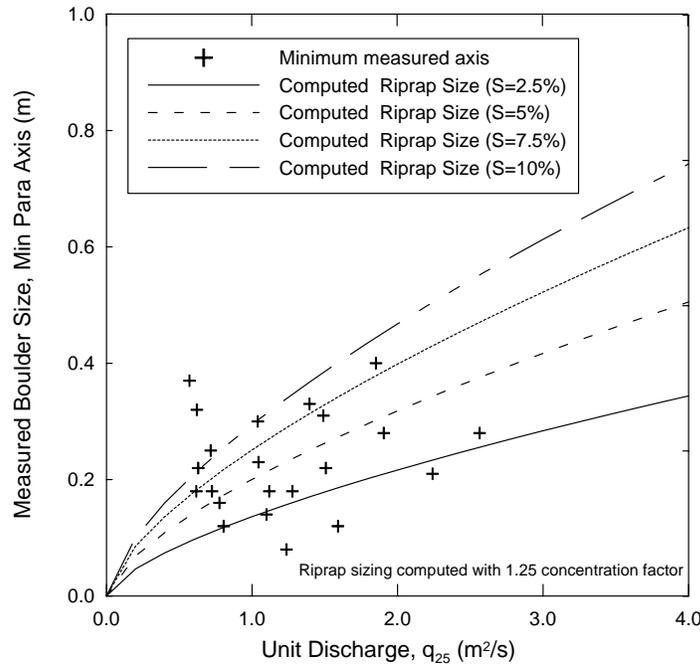


Figure 3. Comparison of measured minimum parallel (to flow) boulder axis and computed D_{30} riprap sizing against unit discharge.

The downstream tailwater control regulates the water-surface elevation of the pool, which in turn affects the energy dissipation and available habitat. The degree of downstream channel contraction is important in terms of function of the step-pool structure. Small amounts of contraction provide little control of the pool tailwater and create high velocities throughout the downstream pool. Too much contraction results in an elevated tailwater that may lead to

sediment deposition within the pool and submergence of the weir. The statistical analysis of the natural steps indicated that the width of the downstream control should be approximately 90 percent of the weir width under low-flow conditions. The maximum pool width is approximately 20 percent larger than the weir width under low-flow conditions.

A force-balance analysis was performed on the boulders comprising two step-pool structures on the Roaring River to evaluate their stability under a range of flows. The fluid and soil forces up- and downstream of the boulder act to produce both driving and resisting moments. The stability of the particles was assessed by the ratio of the driving to resisting moments, otherwise known as the safety factor. Stability of the individual particles was calculated for the 2-, 5-, 10-, 25-, 50-, and 100-year discharges. The depth of burial and location of the pivot point were varied to examine stability under varying configurations. The results of the analysis indicate that the step-pool structures are stable at flows up to the 100-year event under their current configuration because of the arrangement and size of the boulders comprising the step structure. Stability is provided by their inherent mass, and additional stability is gained by interlocking amongst the boulders.

An analysis of the hydraulic effectiveness of step-pool structures was performed using the low-drop, grade-control structure criteria presented Little and Murphy (1982). At discharges equal to and greater than the 2-year flow event, the majority of step-pool structures do not function as low-drop grade-control structures and become submerged with computed Froude numbers dropping below 1.

Dimensionless multiple regression equations were developed (from the natural step-pool structures) for determining pool length and pool depth. Data, including unit discharge, step height, and channel slope were analyzed with the best subsets regression and multiple regression procedures (Jandel Corporation, 1995). Active channel width (ACW) was used as a basis for nondimensionalizing the data at each site. The ACW represents the average of the cross-section topwidths at the 2-year discharge for each site. The equations were applied to the four man-made boulder steps on the San Miguel River. In the man-made structures, the predicted pool length was well correlated with the measured values. However, the measured depths were large compared to the predicted depths. This is attributed to the difference in mobility of the channel bed material between the San Miguel River and the natural step-pool study sites from which the equations were developed. The bed materials of the pools in the natural structures is underlain by boulders that limit scour depth, whereas the pools of the man-made structures are finer grained, and therefore have greater scour potential even though the relative sizes of the bed material are similar in both cases. This has important implications for the stability of structures built in channels with mobile bed material. Large scour depths below the weir may cause undermining of the boulders and create structure instability.

Comparison of the physical characteristics in the downstream pools, of both natural and man-made structures, with published values of preferred trout habitat, showed that these pools meet trout habitat preferences under low-flow conditions (Figure 4).

Design Procedure

The results from the analysis of field data gathered at the study sites were used to develop a design process for sizing step-pool structures. Spacing and step height criteria for constructed step-pool structures for grade-control purposes require a detailed investigation of the expected equilibrium gradient of the channel (Mussetter, 1982; Resource Consultants & Engineers, Inc., 1994).

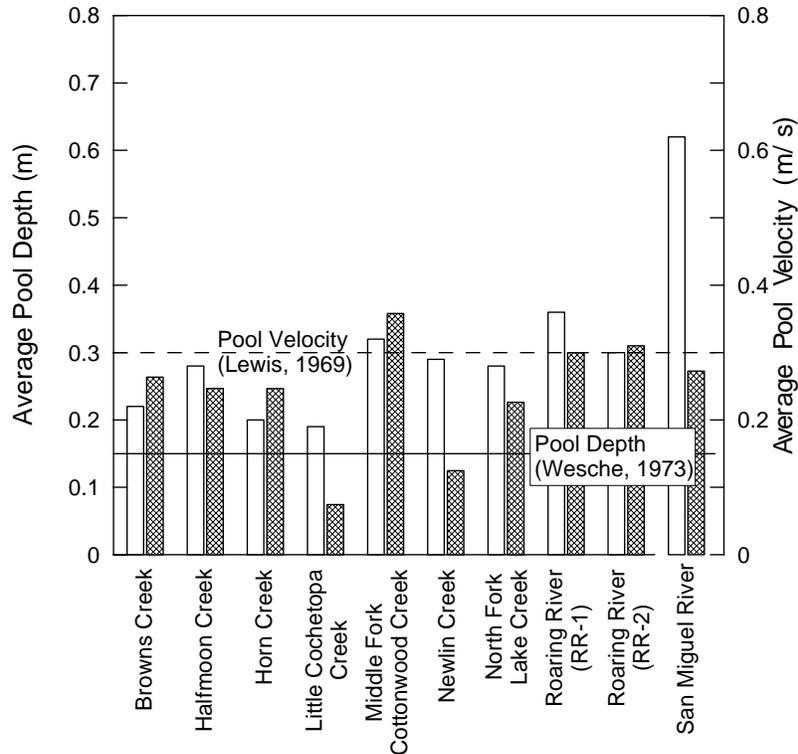


Figure 4. Average pool depth and velocity (cross hatched) at the study site locations during low flow.

Step height is the independent variable in the design process. When constructing step-pool structures for channel stabilization purposes, the drop height will reflect the elevation loss that must be accommodated to stabilize the channel while meeting the low-drop criteria up to the 2-year discharge. Similarly, the step height may be chosen to determine habitat value in the downstream pool. The design process is as follows:

1. Determine the step height (H) required for the step-pool structure.
2. Calculate the existing average channel slope of the reach.
3. Calculate the active channel width for the reach.
4. Calculate the weir width.
5. Determine the 2- and 25-year unit discharge for the weir.
6. Calculate the minimum (D_{30}) boulder size using the COE (1991) steep-slope, riprap design procedures (Equation 1) with the 25-year unit discharge. The minimum rock size may have to be increased to allow for burial. This will reduce the potential for local scour on the downstream side of the weir.

$$D_{30} = \frac{1.95 S^{0.555} q^{\frac{2}{3}}}{g^{\frac{1}{3}}} \quad (2)$$

where S is the channel slope, and q is the unit discharge.

7. Compute the pool length using the Equation (3):

$$\frac{\text{Pool Length}}{\text{ACW}} = 0.409 + 4.211 \frac{H}{\text{ACW}} + 87.341 \frac{S_0 q_{25}^{\frac{3}{2}}}{\sqrt{g} \text{ACW}^{\frac{3}{2}}} : R^2 = 0.65 \quad (3)$$

8. Compute the scour depth using the Equation (4):

$$\frac{\text{Scour Depth}}{\text{ACW}} = -0.0118 + 1.394 \frac{H}{\text{ACW}} + 5.514 \frac{S_0 q_{25}^{\frac{3}{2}}}{\sqrt{g} \text{ACW}^{\frac{3}{2}}} : R^2 = 0.69 \quad (4)$$

9. Compute the contraction at the downstream tailwater control for the 2-year discharge event using Equation (5):

$$\text{Effective Width at downstream control} = 0.92 * \text{Weir Width} \quad (5)$$

10. Compute the maximum pool width at the downstream tailwater control for the 2-year discharge event using Equation (6):

$$\text{Maximum Pool Width} = 1.20 * \text{Weir Width} \quad (6)$$

11. Compute the bank elevation to ensure all flow up to the design discharge is confined within the channel at the weir.

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