Boulder Clusters

by Craig Fischenich[1] and Rebecca Seal[1]

February 2000

Complexity	Environmental Value	Cost
Low — Moderate — High	Low — Moderate — High	Low — Moderate — High

OVERVIEW

Boulder clusters are groups of large rocks (>10 in. diameter) placed in a stream to improve habitat (Figure 1). Flow separation around the boulders leads to the formation of eddies or vortices in their wake. These vortices diffuse sunlight and create overhead cover for fish. They also generate scour that develops pockets of deeper water and associated coarse substrate that add to the physical diversity of a stream reach.

Boulders and the turbulence and scour they create are among the types of habitat used by both juvenile and adult fish, particularly salmonids. Preferred summer microhabitat for juvenile salmonids consists of deep water in conjunction with submerged cover. This cover is used to elude predators. Adult fish also rest and hide in the scour pools. Spawning adults appear to select spawning sites based on the closeness of cover.

Evaluations of fish habitat improvement projects have shown a high variability in the benefits of instream boulders. This variability is due to differences in fish seeding levels, species and ages of fish, season of year, the design of the project, time since implementation, and sampling method.

PLANNING

The first step in the planning process is to determine, a priori, if cover and diversity are limiting habitat characteristics in the stream.

Figure 1. Boulder clusters

If they are, fish density should be adequate to completely use existing and potential habitat. Efforts to increase fish abundance or population health could be unsuccessful or premature if too few fish are available to occupy the habitat created by the boulders.

Critical levels of fish abundance, either in density or biomass, are difficult to ascertain. Existing abundance can be estimated by systematic electrofishing or pole seining of diverse reach segments. There is no definitive minimum level of abundance, which would vary as a function of stream benthic productivity, complexity of rearing habitat, and targeted fish species, among other factors.

The potential for boulder clusters is usually determined by a project team that includes

[1] USAE Research and Development Center, Environmental Laboratory, 3909 Halls Ferry Rd., Vicksburg, MS 39180

a fish biologist knowledgeable in local stream conditions and habitat requirements for the targeted species. The team relies on interpreting data compiled from a site inspection to determine the viability of using boulders to enhance habitat. The stream should be inspected during low flow conditions and, if possible, maximum and normal flow to record the dominant thalweg, unstable sections, and to quantify existing habitat. Each reach should be classified into pool, run, or riffle, estimating the following:

1. Length of pool, run, or riffle.
2. Mean depth of each habitat class.
3. Percent instream protruding boulders.
4. Percent instream logs and debris.
5. Percent overhead cover > 3 ft from the surface.
6. Local and cross section average velocity.
7. Substrate composition (% by class or gradation).

Fish and invertebrate sampling should ideally be conducted in conjunction with the site inspection. Because the inspection effort outlined above requires survey techniques, concurrent collection of the information needed for design is recommended. The study team must evaluate the collection of information in the context of the project objectives to make an informed decision regarding the applicability of boulder groupings to the site and project. Quantitative tools that help in the habitat evaluation include: Fish Index of Suitability (Habitat) (FIS(H)), Habitat Evaluation Procedure (HEP), Physical Habitat Simulation Model (PHABSIM), and Riverine Community Habitat Assessment and Restoration Concept (RCHARC).

FIS(H) and RCHARC can be used in conjunction with a selected reference reach to determine the number of boulder groupings needed to match the habitat distribution in the reference reach. HEP and PHABSIM, on the other hand, require more direct analysis of the habitat benefits

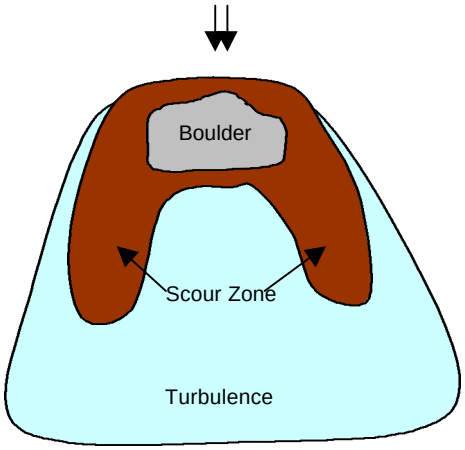

Figure 2. Scour pattern around a boulder

associated with the principal components of boulder habitat: turbulent cover, scour pockets, substrate, and physical cover.

Site Selection for Boulder Groupings

Boulder clusters can be prescribed for sections of stream reaches that have:
a) a dominance of riffle over pool and
b) riffles comprised of coarse gravel to cobble substrate, with few boulders and other associated cover. Alternatives should emphasize multiple boulder groupings in conjunction with other designs, such as wing deflectors and bank cover, to ensure stability of the thalweg and optimize benefits. Additional considerations for the selection of potential boulder sites include:

1. Use boulders only where cover and/or diversity is limited.
2. Use fewest boulders possible to attain desired habitat.
3. Boulders should occupy <10% of flow area at bank-full flow.
4. Avoid pools and slow runs. Velocity should exceed 4 fps at bank-full flow.
5. Not recommended for use in sand bed streams.
6. Avoid placement in braided, unstable sections.
7. Use boulders sized for stability at bank-full flow.
8. Avoid placement of boulder groupings near the upper end of riffles.

9. Allow sufficient (e.g., 16 ft) riffle leading into structures to maximize insect drift.
10. Concentrate boulders in or near channel thalweg to ensure habitat availability during low flow.

DESIGN

The primary design considerations for boulder clusters are a) the number, configuration, and location of the structures, and b) the size of the boulders needed for stability. The hydraulic impacts of the boulders should also be ascertained when habitat benefits must be quantified or the potential exists for adverse impacts due to increased velocities or water surface elevations.

Number, Configuration, and Location

Three to five boulders in a triangular configuration in staggered groups or clusters along the riffle or very shallow run appear to be most effective because each group guides turbulent "overhead cover" into a downstream group. To maximize turbulence and scour, boulders should be well-spaced (about 1 diameter between boulders). Boulders placed in the wake of an upstream boulder have minimal benefits, so successive downstream boulders should be placed at the periphery of the wake of upstream boulders. Armoring of banks may be necessary if boulders are placed within a few feet of the banks. Additional guidance is summarized in the PLANNING section. Figure 3 shows the relation between habitat benefits and the number of boulders.

Boulder Stability

A boulder immersed in flowing water is subject to the hydrostatic surface force of pressure, the body forces of weight (F_W) and buoyancy (F_B), the additional hydrodynamic forces of pressure (normal to the body surface) and viscous shear forces (tangential to the body surface) (Figure 4).

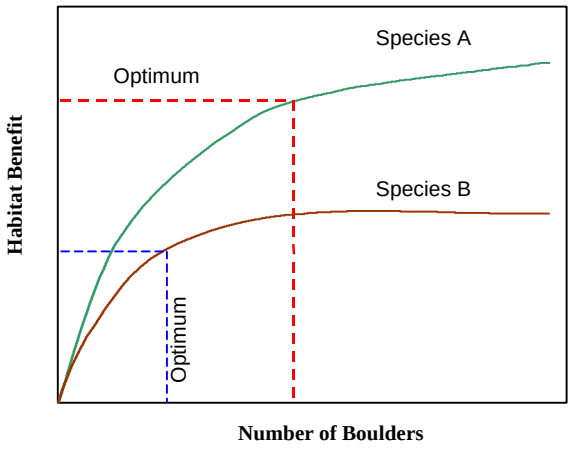

Figure 3. Generalized relation between habitat benefits and number of boulders

The normal and tangential hydrodynamic forces can be resolved into the drag force (F_D), and the lift force (F_L). If the immersed body is resting upon the streambed, there is a friction force (F_R) that acts opposite to the direction of flow. A boulder will remain at rest as long as the active forces of drag, lift, and buoyancy are less than the resistive forces of weight and friction.

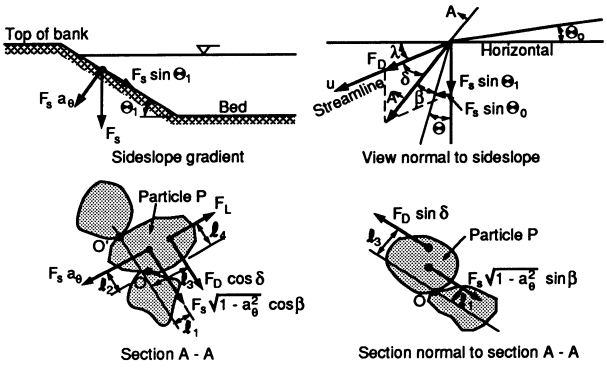

Figure 4. Forces on a boulder

Because both drag and lift are functions of the approach velocity raised to the second power, velocity or shear stress is sometimes used as a surrogate for stability analyses. Values of critical velocity and shear stress for boulders, cobbles, and coarse gravels are provided in Table 1. For fully turbulent flow over a rough horizontal surface with the boulder fully immersed, incipient motion occurs when:

$$d_s = \frac{(18\ y\ S_f)}{(G-1)} \qquad (1)$$

where

ds = minimum boulder diameter (ft)
y = channel full flow depth (ft)
S_f = friction slope
G = specific gravity of boulder (~2.65)

Table 1. Threshold Conditions
(adapted from Julien (1995))

Class name	ds (in)	f (deg)	t_{*c}	t_c (lb/sf)	V_c (ft/s)
Boulder					
Very large	>80	42	0.054	37.4	25
Large	>40	42	0.054	18.7	19
Medium	>20	42	0.054	9.3	14
Small	>10	42	0.054	4.7	10
Cobble					
Large	>5	42	0.054	2.3	7
Small	>2.5	41	0.052	1.1	5
Gravel					
Very coarse	>1.25	40	0.050	0.54	3
Coarse	>0.63	38	0.047	0.25	2.5

Table 1 and Equation 1 can be useful for a preliminary analysis to ascertain the approximate dimensions of a stable boulder for the project site. However, more detailed analyses are generally warranted. The most universally applicable approach is a moment stability analysis. In a moment stability analysis, a single boulder is evaluated based on the ratio of moments resisting overturning to moments promoting overturning of the particle about the point of contact of the rock with an adjacent boulder or the bed of the stream.

The ratio of moments that resist overturning of the particle, M_R to moments that promote overturning M_P defines a safety factor $SF = \sum M_R / \sum M_P$, that provides an index of particle stability. Ratios larger than unity indicate a stable riprap particle; ratios less than unity indicate an unstable particle; and ratios equal to unity indicate a neutrally stable particle. The moment stability analysis procedure presented herein is for the general case, allowing for the analysis of boulders placed on side slopes and including streamlines not parallel to the channel (i.e., accounting for secondary currents).

Figure 4 illustrates the forces acting on a boulder resting on the bed or bank with an across-stream inclination angle q_1 and a bed slope of q_2. For a water surface slope less than 0.1, the buoyancy force can be subtracted from the boulder weight to give the submerged weight of the boulder, $F_S = F_W - F_B$. The other forces are as defined in the first paragraph of this section. The streamline is allowed to deviate from the horizontal by an angle λ to account for secondary currents (in a straight section, $\lambda = 0$). The direction the boulder would move if destabilized is described by the angle β from a vertical line on the embankment plane. Using simple geometric relations, we define:

$$a_q = \sqrt{\cos^2 q_1 - \sin^2 q_0} \qquad (2)$$

and

$$\tan q = \frac{\sin q_0}{\sin q_1} \qquad (3)$$

Using these two relations, given the angle of repose for the boulders ϕ ($\phi \cong 42$), and defining $A=(l_4/l_2)(F_L/F_S)$ and $B=(l_3/l_4)(F_D/F_S)$ (where the moment arm lengths l_n are defined in Figure 4), the following four equations can be successively solved to determine the safety factor:

$$SF = \frac{a_q \tan f}{h_1 \tan f + \sqrt{1-a_q^2}\cos b} \qquad (4)$$

$$h_1 = h_0\left[\frac{(A/B)+\sin(l+b+q)}{1+(A/B)}\right] \qquad (5)$$

$$h_0 \cong \frac{18 t_0}{(g_s - g_w)\, d_s} \qquad (6)$$

$$\beta = \tan^{-1}\frac{\cos(\lambda+\theta_1)}{\left[\frac{(A+B)\sqrt{1-a_q^2}}{Bh_0\tan\phi}+\sin(\lambda+\theta_1)\right]} \quad (7)$$

From a practical standpoint, A = B can be used because the equations are not very sensitive to this ratio. These equations are only applicable when $\lambda \geq 0$. If the boulders are placed on the inside of a bend and the secondary currents are up the bank ($\lambda < 0$), a different equation is required. An EXCEL spreadsheet solving these equations for an example with ds = 2 ft, λ = 15 deg, θ_1 = 20 deg, horizontal bed slope, and ϕ = 42 deg (from Table 1) is shown as Table 2.

Users of the spreadsheet enter a range of shear stress values and select the value corresponding to SF = 1.0. This value can be used for design purposes for a reconstructed channel or, if not consistent with computed shear stress values in the channel, a different boulder size can be selected. Again, boulders will be stable when SF ≥ 1.0. Equations in the spreadsheet are given below.

Table 2. Example Stability Spreadsheet

ds	*(ft) =*	*2*
f	*(deg) =*	*42*
q_1	*(deg) =*	*20*
q_2	*(deg) =*	*0*
l	*(deg) =*	*15*

(1) t_c *(lb/sf)*	*(2)* h_0	*(3)* β	*(4)* h_1	*(5)* SF
6.00	*0.612*	*32.777*	*0.533*	*1.103*
6.25	*0.638*	*33.660*	*0.558*	*1.075*
6.50	*0.663*	*34.514*	*0.584*	*1.048*
6.75	*0.689*	*35.339*	*0.609*	*1.022*
7.00	*0.714*	*36.137*	*0.635*	*0.998*
7.25	*0.740*	*36.908*	*0.661*	*0.974*
7.50	*0.765*	*37.653*	*0.687*	*0.952*
7.75	*0.791*	*38.373*	*0.712*	*0.930*
8.00	*0.816*	*39.070*	*0.738*	*0.909*

Equations for the computations follow:

Col2 =(0.204/d_s)*(Col1)

Col3 =ATAN(COS(θ_2*PI()/180)/((2*SIN(θ_1*PI()/180))/((Col2)*TAN(ϕ*PI()/180))+SIN(θ_2*PI()/180)))*180/PI()

Col4 =(Col2)*((1+SIN((θ_2+(3))*PI()/180))/2)

Col5=COS(θ_1*PI()/180)*TAN(ϕ*PI()/180)/((Col4)*TAN(ϕ*PI()/180)+SIN(θ_1*PI()/180)* COS((Col3)*PI()/180))

CONSTRUCTION

Placement methods for boulders depend upon site access and equipment availability. Placement from the upper bank with a large excavator incorporating a "thumb" attachment is the preferred method. Boulders should never be end-dumped from the bank into the stream.

In coarse substrate, pre-excavation of material at lower sides and downstream of boulders may be necessary to create "pockets," though the designer must ensure that excavation does not compromise an armor layer.

OPERATION AND MAINTENANCE

Operation and maintenance requirements for boulder clusters are minimal. Clusters should be inspected annually to determine stability. Boulders that have dislodged and moved a few feet need not be relocated unless they are causing stability problems. More significant movement is indicative of design deficiencies, and harvesting and relocating boulders into zones of lower velocity should be considered. Shifts in the channel thalweg that cause boulders to perch during low flow conditions should also be regarded as an inducement to relocate boulders.

Fish and invertebrate sampling to determine the effectiveness of the boulder clusters is always recommended.

APPLICABILITY AND LIMITATIONS

Techniques described in this technical note are generally applicable to stream restoration projects that include fish habitat improvements as an objective. The use of boulder clusters is generally limited to streams with coarse gravel (or larger) substrate. Approximations in the

analytical techniques imply that the specific weight of the boulders be approximately 2.65. Stream slopes must not exceed 0.10 for the equations to remain valid.

The moment stability equations are applicable both to single boulders and to boulders placed in a blanket. Values for A and B are adjusted according to the moment arm lengths (l_n) for each case.

Boulder cluster benefits are highly variable. Little or no benefit may be derived from the placement of these features in the stream system. Boulders can present a safety hazard, and designers are cautioned to consider recreational boating requirements prior to selecting sites for boulder placement.

ACKNOWLEDGEMENTS

Research presented in this technical note was developed under the U.S. Army Corps of Engineers Ecosystem Management and Restoration Research Program. Messrs. E.A. (Tony) Dardeau, Jr. and Jerry L. Miller of the Environmental Laboratory, and Dr. Stephen L. Maynord of the Coastal and Hydraulics Laboratory provided technical reviews.

POINTS OF CONTACT

For additional information, contact the author, Dr. Craig Fischenich, (601-634-3449, *fischec@wes.army.mil*), or the manager of the Ecosystem Management and Restoration Research Program, Dr. Russell F. Theriot (601-634-2733, *therior@wes.army.mil*). This technical note should be cited as follows:

> Fischenich, C., and Seal, R. (1999). "Boulder clusters," *EMRRP Technical Notes Collection* (ERDC TN-EMRRP-SR-11), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *www.wes.army.mil/el/emrrp*

REFERENCE

Julien, P., 1995. Erosion and Sedimentation. Cambridge University Press, New York, NY.