BOULDER CLUSTERS

1 DESCRIPTION OF TECHNIQUE

This technique describes the strategic placement of large immobile boulders (>1 cubic yard) and boulder clusters within homogenous sections of streams to increase or restore structural complexity and hydraulic diversity. Plane bed stream reaches may occur naturally or as a result of both direct and indirect human activities that simplify a channel. Direct human activities may include modifications of the channel (e.g. levee construction, bank hardening, channel straightening, dredging, wood removal). Indirect human activities alter watershed processes by reducing the source of roughness elements (e.g., trees) for delivery to the stream or, on a larger scale, contribute to an increase in peak flows that often leads to channel incision and scouring out of roughness elements from the reach (e.g. long-time deforestation, urbanization). The loss of roughness elements and simplification of the channel results in a loss of habitat diversity and complexity, that has a pronounced effect on the abundance, composition, and distribution of aquatic biota inhabiting that area. Structural and hydraulic diversity is important to a broad variety of organisms including aquatic insects, fish, amphibians, mammals, and birds. Much of the impetus behind the use of this technique, however, centers on providing holding and rearing habitat for fish, principally salmonids[1], and on sorting bed material to improve fish spawning habitat.

Boulder placement has been used successfully throughout North America to enhance fish habitat. Though this discussion is limited to placement of individual boulders and clusters of boulders, boulders may also be used as a component of larger structures to concentrate scour (see *Porous Weirs*), provide grade control (see *Drop Structures*), provide bank protection (see *Barb, Groin, Riprap*, and *Rock Toe* techniques in the Integrated Streambank Protection Guidelines[2]), and to provide ballast for logs (see *Placement and Anchoring of Large Wood* appendix).

This technique provides some immediate benefits (e.g., cover, refuge) and works in conjunction with stream flow to create and maintain additional habitat. It has short- or long-term effectiveness, depending on the stability of the channel and site conditions.

2 PHYSICAL AND BIOLOGICAL EFFECTS

Placement of individual boulders and boulder clusters within the stream channel creates a diversity of water depth, substrate, and velocity, thereby increasing habitat diversity of an otherwise plane bed stream. Increased diversity is evident immediately after boulder placement and improves over time as substrate is scoured and sorted during high flow events. Diverse habitats can support a greater diversity of species and age classes than homogeneous habitats; of course use of these habitats depends on the species present in the system. Boulders provide cover in the form of interstitial spaces between the boulders, relatively deep water, air bubbles, and turbulence[3] and they create water velocity gradients, where slow water velocities occur in close proximity to faster ones. As cited by Ward[4], the presence of water velocity gradients is desirable for many fish species, including both juvenile and adult salmonids, because it allows them to maintain a position near the faster, food-delivering current without expending much energy. The enhanced structural complexity associated with boulders also allows for increased fish densities within these energetically favorable environments. In the absence of sufficient refuges from higher velocity, the energetic costs to fish occupying such habitat increase dramatically. Moreover, such velocity-homogeneous habitats tend to be food poor. Both of these factors translate to fish that are in poorer physical condition and have diminished survival.

In addition to benefiting fish, the microhabitat created by boulders provides localized refuge or reproductive habitat for a variety of other aquatic organisms. For example, the downstream face of a boulder, which experiences lower velocities, is often preferably selected as an attachment site for caddis flies, mayflies, and stoneflies, dominant invertebrates in many stream systems.

Boulders confine and direct flow, typically creating bed and/or bank scour in the immediate vicinity of the stones and depositing sorted bed material downstream[5]. These scour pockets provide cover and forage habitat for fish during low flows. Whether or not scour occurs depends heavily on sediment transport dynamics. Scour will occur only where the shear stress induced on the bed is sufficient to scour out the bed material. For this reason, scour pools may not develop in backwatered channel reaches, channels comprised of relatively large bed material (e.g., cobbles), and in low energy sites such as certain off-channel or side-channel habitats. The benefits of boulder clusters will also be diminished in channels that carry relatively high levels of fines that tend to fill the interstitial spaces. Where such conditions occur, upslope rehabilitation techniques may be required before, or used in conjunction with, boulder cluster placement to reduce sediment delivery rates and insure sediment conveyance is maintained near the boulders. Habitat benefits will be limited to cover in backwatered areas.

Depending on the pattern, spacing, and location of boulders and the degree to which they confine flow, boulders may have a backwater effect on the upstream reach of the channel. Backwater can cause upstream deposition, a localized increase in floodwater stage, and can increase the likelihood of bank erosion and channel avulsion in the area of deposition. This backwater effect may be caused by the boulders themselves or by the boulders in combination with any sediment and wood that becomes racked up against them. Backwater is most likely to occur when boulders are placed at or near the riffle crest. When placed in the lower section of riffles, boulder clusters act to stabilize the riffle crest and transfer scouring forces to the downstream pool. The potential for unanticipated scour, deposition, flooding, and streambank erosion must be considered.

The longevity of benefits provided by boulder placement depends on sediment transport dynamics that, in turn, depend on the hydrologic and sediment regimes of the stream. Benefits provided by boulder placement will be short-term if the boulders become mobile during frequent storm events. But even if the boulders remain in place, their effects may be short-lived if they are placed in deposition zones where they become buried in sediment or in readily scoured material, such as fine-grained or unstable beds. When placed in readily scoured material, boulders will tend to sink into their own scour holes. The lateral stability of the stream reach also plays a factor in project longevity. In dynamic channels, placed boulders may be abandoned as the channel shifts and migrates, or they may end up in unintended locations. In either case, the durability of benefits will depend on the rate of change within the channel.

The placement of boulders may result in disturbance in the form of increased turbidity and rearranging of bed material during construction activity. Construction impacts, and ways to reduce them, are discussed in the *Construction Considerations* appendix. Consideration should be given to the potential habitat impacts to source areas for boulders, access to and from the source area, and to and from the installation site. Access and staging areas may experience short-term impacts and may require reclamation or mitigation. Disturbance will vary with the ease of access, equipment chosen for construction, and the skill of equipment operators.

3 Application

This technique can be used to restore habitat diversity to plane bed streams from which boulders have been removed. (Boulders may have been removed historically to facilitate navigation and wood transport.) It can also be used as an enhancement technique to increase habitat diversity in new channels, naturally plane bed stream reaches, and altered plane bed channels that were historically dominated by wood. Due to the dynamic nature of wood movement in streams, in-stream boulder placement may be a preferred alternative to wood when a static condition is desired (movement of channel roughness elements is not acceptable), wood of adequate size is not available, and when the source of adequately sized wood to the stream will take decades to recover. Boulder clusters should only be applied where a biologic or geomorphic need has been identified.

When identifying potential boulder placement sites, consideration must be given to what locations will provide the most biological benefit. The intent of this technique is to provide cover and favorable holding and rearing habitat for fish while providing a mechanism for substrate scour and sorting. However, sites that are attractive from a biological standpoint may not necessarily be attractive from a hydraulic standpoint (excess scour, degraded bank stability) or may pose an unacceptable level of risk. Thus, site selection will require consideration of both biological and hydraulic conditions.

Boulder placement projects are usually intended to provide habitat benefits on a small (relative to channel size) localized scale. They are most effective in wide, shallow streams with gravel or cobble beds[6]. They are not recommended in fine-grained streambeds as bed scour in the vicinity of boulders may undermine them and cause them to fall or sink into their scour holes . Boulder placements in bedrock channels may not be able to resist shear forces that would propel them downstream. Flosi et al.[7] state that boulders and boulder clusters should be "located in straight, stable, moderately to well-confined, low gradient riffles (0.5 to 1 percent slope) for spawning gravel enhancement and in higher gradient riffles (1 to 4 percent slope) to improve rearing habitat and provide cover". Slopes that exceed 4 percent typically exhibit step-pool channel morphology. Most streams that have a low sediment supply would already have incised into stable boulder step pools or bedrock channels. These channels easily transport incoming sediment downstream. Channels greater than 4 percent that are entrenched or incised into glacial, alluvial or colluvial depositional material provide much more sediment to the channel. These step pool channels are much more unstable and can be associated with debris torrent tracts or active glacial environments that are common in the Northwest. Therefore, channels greater than 4 percent slope start to become inappropriate for boulder placements because they are either already boulder step pool channels with no additional need for boulders or unstable entrenched channels with active bank erosion. Boulder placements would tend to increase bank instability in these environments. Boulder placements in bedrock channels scoured by splash dam activity or large wood removal is an example of a potential project in this gray area between appropriate and inappropriate work gradients. Work in gradients exceeding 4 percent requires a more thorough geomorphic and hydraulic analysis.

Avoid placing boulders in depositional areas, such as aggrading channels or braided channels, as they may be buried in sediment and become ineffective or abandoned during a channel shift. Caution should be exercised in incised or incising channels. In addition to boulder stability concerns, boulder placements in unstable incising beds may create conditions that accelerate lateral erosion. Incised channels that have lower gradients (less than 4 percent) often become laterally dynamic because hydraulic forces are typically confined within an entrenched channel rather than being distributed over the floodplain. This increases hydraulic shear on bank material that can accelerate bank erosion. Boulders may exacerbate this process. Consequently, boulder placement in incised channels requires a greater degree of geomorphic and hydraulic scrutiny to determine consequences and risk needed to form a plan of action.

In watersheds that have become unstable from development, forest management, or other land use activities, boulder clusters, as with any in-stream restoration work, are best used in conjunction with watershed restoration techniques that address the cause of watershed instability. Improving road drainage and stormwater management, revegetating streambanks and unstable slopes, or removing unnecessary and degrading roads to improve natural drainage patterns and limit the increase in peak flow hydrology are examples of upland restoration activities that would facilitate successful channel restoration and boulder applications.

Additional boulder application considerations are provided in Methods and Design.

4 RISK AND UNCERTAINTY

Boulder placements are relatively low risk treatments in streams provided they block a relatively small proportion of the bankfull flow area and thereby limit their hydraulic influence on the channel. However, where boulders, or the bed material and wood that racks up on them, significantly confine a channel or collectively increase the roughness of the reach by a significant amount, the upstream channel may become backwatered, causing deposition (in streams that carry high sediment loads), localized flooding, and bank scour. There is also an increased risk of channel avulsion. Even where the encroachment of boulders on bankfull channel area is low, boulders redirect flow and may cause adjacent or downstream banks to erode.

In some stream channels boulder treatments have a greater degree of uncertainty and risk. The following are examples of situations that point towards a greater degree of complexity, risk or uncertainty.

- *High gradient, confined, or bedrock channels.* Boulder stability will be more difficult to achieve.
- *Channels with high natural sediment loads.* Boulders increase channel roughness. This

could potentially result in sediment deposition and instability near the boulders. This is more likely in lower gradient alluvial streams because sediment transport thresholds are easier to achieve. Non-alluvial steeper channels and incised streams tend to transport incoming sediment much more easily and deposition isn't as likely to occur.

- *Watersheds with changing hydrologic or sediment regimes.* These are deceptive environments because existing channel dimensions and substrate are undergoing change. Assuming existing conditions are stable and designing under that premise will result in failure if elevated sediment and hydrology increase due to present or future development. This is common in urban and suburban growth watersheds.
- *Incised channels.* These channels have been previously disturbed. Understanding what caused the disturbance and recovery processes that are underway are important before adding boulders to the channel. Another factor to consider in incised channels is that boulders can accelerate lateral bank erosion. Whether this is desirable depends on factors such as infrastructure near the site, existing watershed stability, future habitat goals and riparian complexity goals. In previously incised but now vertically stable streams, lateral erosion provides more space to develop channel and riparian complexity. In this sense boulders can provide the same hydraulic and geomorphic influences as large wood material.

These examples underscore the need to understand stream sediment loads, watershed stability, bed and bank mobility, and long-term habitat goals before designing boulder habitat.

4.1 Risk to habitat

Boulder placements typically pose a low risk to existing habitat. Potential impacts would include temporary loss of habitat value associated with rearranging gravels through scour or burial of habitat through deposition. However, in these instances, habitat lost will probably be offset by habitat or habitat value gained, and therefore risks are only short-term and should not persist beyond the first high flow event. Risk to habitat increases if boulders create upstream backwater that causes large-scale deposition, potentially leading to chronic dredging of the channel or to channel migration or avulsion.

4.2 Risk to infrastructure and property

When boulders are located relatively low in the channel profile and don't direct flow into banks, boulders pose minimal risk to infrastructure and property. However, there is the risk of excessive bed or bank scour, catching of debris, and upstream deposition causing a localized increase in flood stage or lateral channel migration that places nearby infrastructure at risk.

4.3 Risk to public safety

Risk to the safety of boaters associated with physical obstructions in the stream and resultant channel hydraulics is a concern. When possible, consult with the local boating community to educate, inform and collaborate.

4.4 Uncertainty of technique

Though there is a relatively low risk of boulders being transported far downstream, there is a fairly high degree of uncertainty in boulder placement design and performance. Boulder placement design ideally should consider sediment budgets and local hydraulic interaction between complex boulder shapes and flow vectors that vary with discharge. But both of these evaluations can be complex and uncertain, and typically require a level of effort that is unjustified in light of the low risks associated with typical applications. Even if boulders perform hydraulically as anticipated, the anticipated biologic benefits may not be realized or they may be shorter-lived than expected.

5 METHODS AND DESIGN

5.1 Data and Assessment Requirements

Although boulder placement has been successful in habitat creation, the risk of inadvertently causing problems should not be ignored. Consider the factors outlined below when planning and designing boulder placement projects. If needed, consult with a fisheries biologist, hydrologist and/or geomorphologist to help answer questions and provide guidance. While the primary intent of introducing boulders may be to create habitat, one must carefully consider the geomorphic, hydraulic, and biologic ramifications associated with the introduction of large roughness elements.

The amount of data collection and assessment required will be dictated by the project scope, availability of existing information, and by the degree of acceptable risk in implementation. The *General Design and Selection Considerations for In-Stream Structures* includes a discussion of the minimum data and analyses typically required for in-stream structure placement. Those and additional requirements relevant to boulders are listed below.

- *What are the objectives of boulder placement?* Are boulder clusters the best alternative to meet those objectives?
- *Conduct a biological assessment.* What species are present in the area and what are the limiting factors affecting their growth and survival? Document existing habitat features and use. This assessment is important to determine whether the treatment has a chance of relieving those limiting conditions and yielding the desired biological effects.
- *Document baseline conditions of the channel and bed material.* Are they appropriate for the use of Boulder Clusters (refer to Section 3, *Application*)? Such an analysis may include:
    - Evaluation of existing flow patterns. How will boulder placement change them?
    - Dominant substrate
    - Channel gradient. The shear stress on the bed and banks of the channel increase with channel gradient. This increases the potential for boulder transport and bed and bank scour. Steeper streams are more powerful and can do more work per unit discharge.
    - Cross-section survey(s)
    - Condition of the banks. Are they relatively stable or actively eroding?
    - Degree of channel entrenchment. The depth of flow and, thus, shear stress on the bed and banks of the channel during high flow events increase with the degree of entrenchment. This increases the potential for boulder transport and bed and bank scour because velocity and depth have increased along with the ability to move larger and greater sediment volumes.
    - General assessment of the lateral and vertical stability of the channel and the

overall stability of the watershed. Is the channel aggrading or incising in the vicinity of the site? Is the watershed unstable and at risk for increased debris flow activity?
  - Additional baseline data may be required for any monitoring planned at the site. The scope and nature of such an assessment depend upon monitoring objectives. It may include, but is not limited to, documentation of fish presence and abundance at treated and control sites, fish use of the area, spawning gravel quality, pre-construction bed topography survey, as built survey, or a qualitative description of habitat and habitat complexity, among other things.
- *Conduct a scour assessment to determine the minimum design depth of boulders, estimate likely pool habitat development, and identify any threat to infrastructure.* In low risk projects, observing the depth of scour associated with other in-stream structures may be sufficient to estimate the likely depth of scour associated with boulder placement. In higher risk projects, a scour analysis may be necessary.
- *Evaluate boulder mobility*. What is the necessary design life or design flow of the structure? What kind and size of material will be necessary to meet those design criteria? In low risk projects, determining the size of boulders currently maintained in stream reaches with similar characteristics (e.g., width, depth, slope, flow, degree of confinement) may be sufficient. In higher risk projects, incipient motion and scour analyses will likely be necessary as part of design.
- *Evaluate access and materials availability*. These impact the type of equipment used, the construction schedule, and the cost of the project. What impacts are likely to occur as a result of ingress and egress of equipment and materials? Will in-stream and riparian site conditions permit construction? Will the cost or availability of materials limit the design?
- *Document the location and nature of in-stream and nearby infrastructure that may benefit or be harmed by the proposed structure.* This is best done in conjunction with developing good plan, profile and cross-section drawings of the site and reach. The presence of infrastructure will likely place limitations upon flow redirection and the degree of allowable backwater.
- *Will the project adversely affect recreational navigation*? What measures can be taken to minimize public safety risks?
- *What are the potential impacts to upstream, downstream, and adjacent habitat, fish and wildlife, infrastructure, and public safety*? What is the probability of those impacts occurring? What factors influence that risk (e.g., degree of channel confinement, slope, bedload, high flow events, material selection)? What can be done to minimize the risk?
- *Develop a plan view sketch or contour map, as necessary, to illustrate current and proposed conditions and boulder placement.*

Projects with a greater degree of complexity, risk or uncertainty (refer to Section 4, *Risk and Uncertainty*) should have project site hydrology, scour analysis, hydraulic analysis and sediment transport characteristics completed before boulder project designs are implemented. Such projects may require a reach-scale assessment. A site scale assessment should be sufficient for design and monitoring of isolated boulder or boulder cluster placements in low risk stable channels as such placements typically do not have reach-scale impacts.

Adjacent reaches with natural analogs can provide very useful design information, including:

- Minimum boulder size
- Spacing between boulders in a cluster
- Spacing between boulders and banks, or effective location within the channel
- Boulder density
- Boulder pattern and orientation
- Anticipated effects, including scour and deposition zones and depths

5.2 Boulder Placement

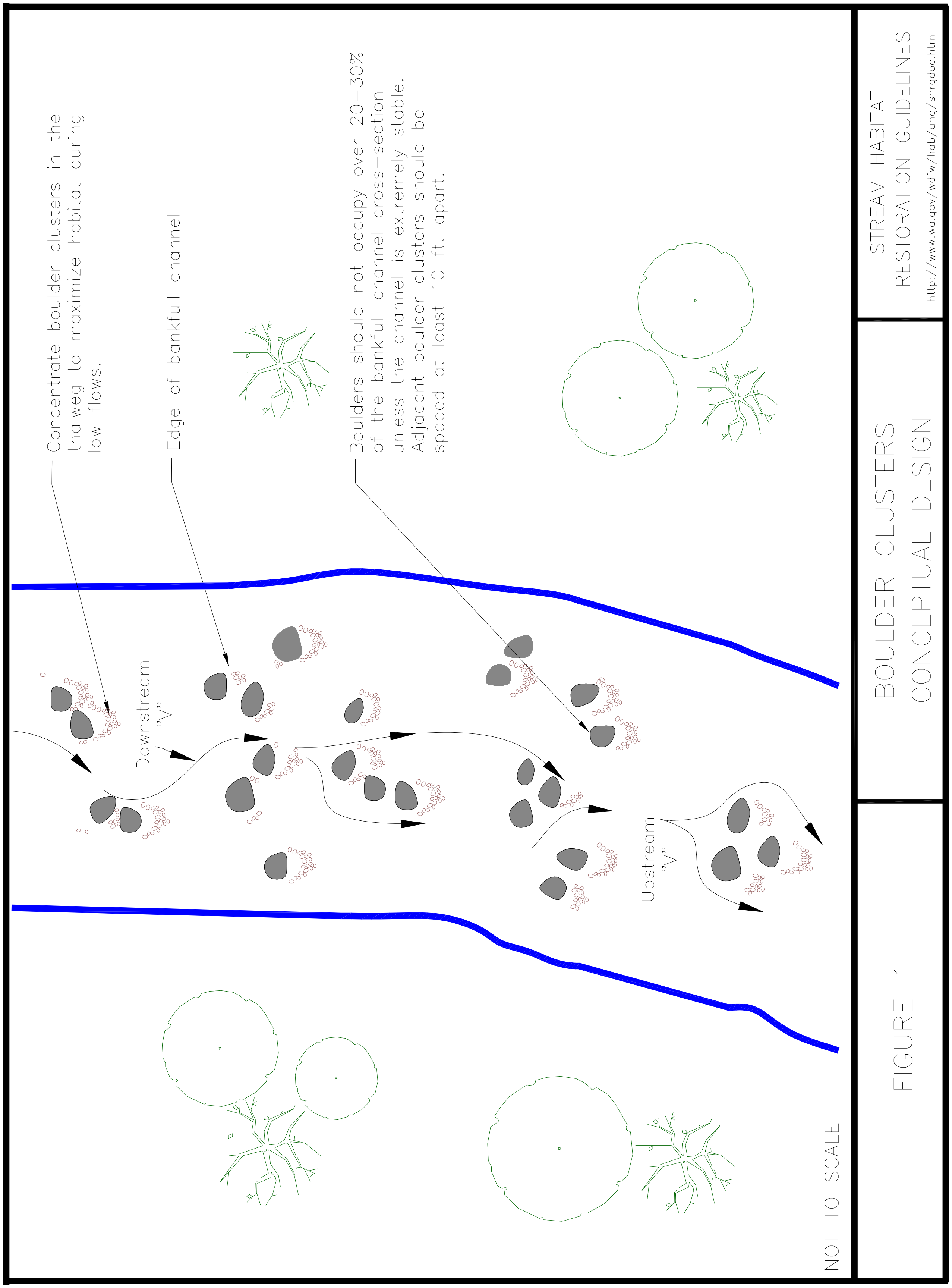
Generally, boulders should be placed in random patterns that replicate natural stream conditions and do not substantially modify overall stream hydraulics. By keeping the hydraulic influence of boulders to a low or moderate level, the designer can create local scour while minimizing the risk of unintended consequences such as excessive bed or bank scour, debris collection, upstream deposition and backwater, higher water surface elevations, and increased risk of channel avulsion. To limit their hydraulic influence, boulders should not be allowed to block a significant portion of the channel cross-section and should be kept relatively low in the channel profile. As cited by Johnson and Stypula, the Oregon State Highway Division[8] suggests that boulder placements not block more than one-third of the bankfull channel area at any cross-section. Johnson and Orsborn[9] suggest limiting bankfull area blockage to 20 to 30 percent. The Federal Highway Administration[10] recommends that a maximum of one fifth of the low flow capacity should be reduced if the gradient of the stream channel is less than three percent. It is recommended that boulders be completely submerged during bankfull discharge.

Boulders can trap and retain wood on the upstream side of the boulders. This can create excellent rearing habitat around the boulder. During high flow events, accumulated wood will float over the top of the boulder and downstream as stage rises, provided the boulders are completely submerged. If overtopping flows occur on a relatively frequent basis (e.g., bankfull flow), it will prevent a large buildup of wood and reduce flood and bank erosion risk. However, if boulders extend to or above the bankfull elevation, wood may not be dislodged and instead may accumulate, thereby increasing the hydraulic and backwatering impacts of the structures which may or may not be desirable. In high-risk situations, the potential scour and backwater effects and potential interaction of wood can be quantified with the use of hydraulic models. A design elevation for the boulders can then be determined so as to limit undesirable consequences. Calculation of scour and backwater are detailed in the *Hydraulics* appendix.

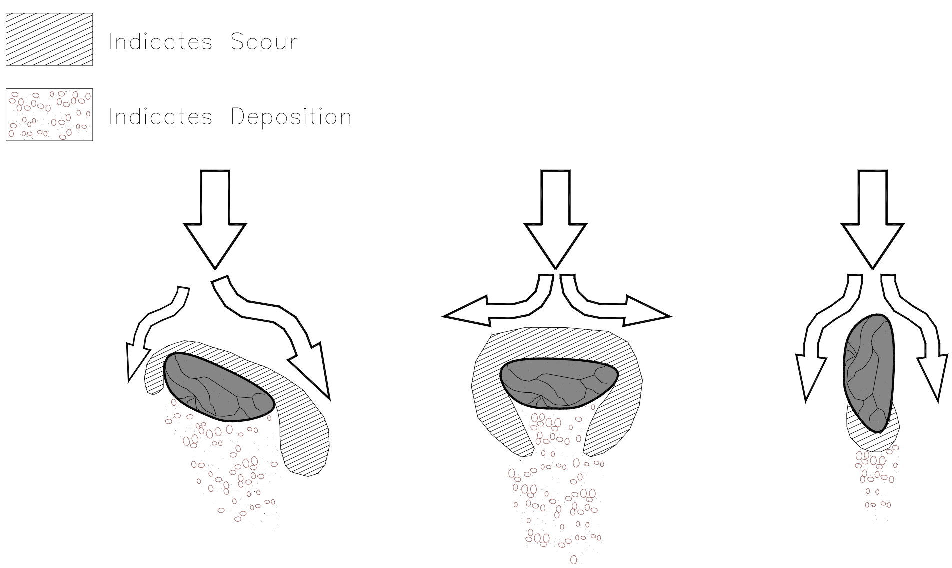
Boulder location is also a factor in the likely occurrence of upstream deposition and channel avulsion. Ward states that boulder clusters placed at or near the riffle crest are more likely to cause aggradation and diversion than those placed further downstream. Boulders placed in the bottom half of riffle habitats will tend to be more stable, less likely to fill in with bedload, and less likely to create large scour holes. Boulders placed near the thalweg of the stream, typically within the middle two quarters of the channel width, will maximize the availability of boulder-created fish habitat during low flow.

Boulders are most frequently installed as a clustered arrangement of several individual boulders due to the increased habitat benefits they provide over single boulders . Groups of boulders create a greater range of velocity and depth conditions and more abundant living space than a single boulder can; there are many void spaces in between boulders that provide velocity refuge and cover that don't exist with a single boulder. Rock clusters also provide a greater opportunity to catch and trap wood material if that is desired.

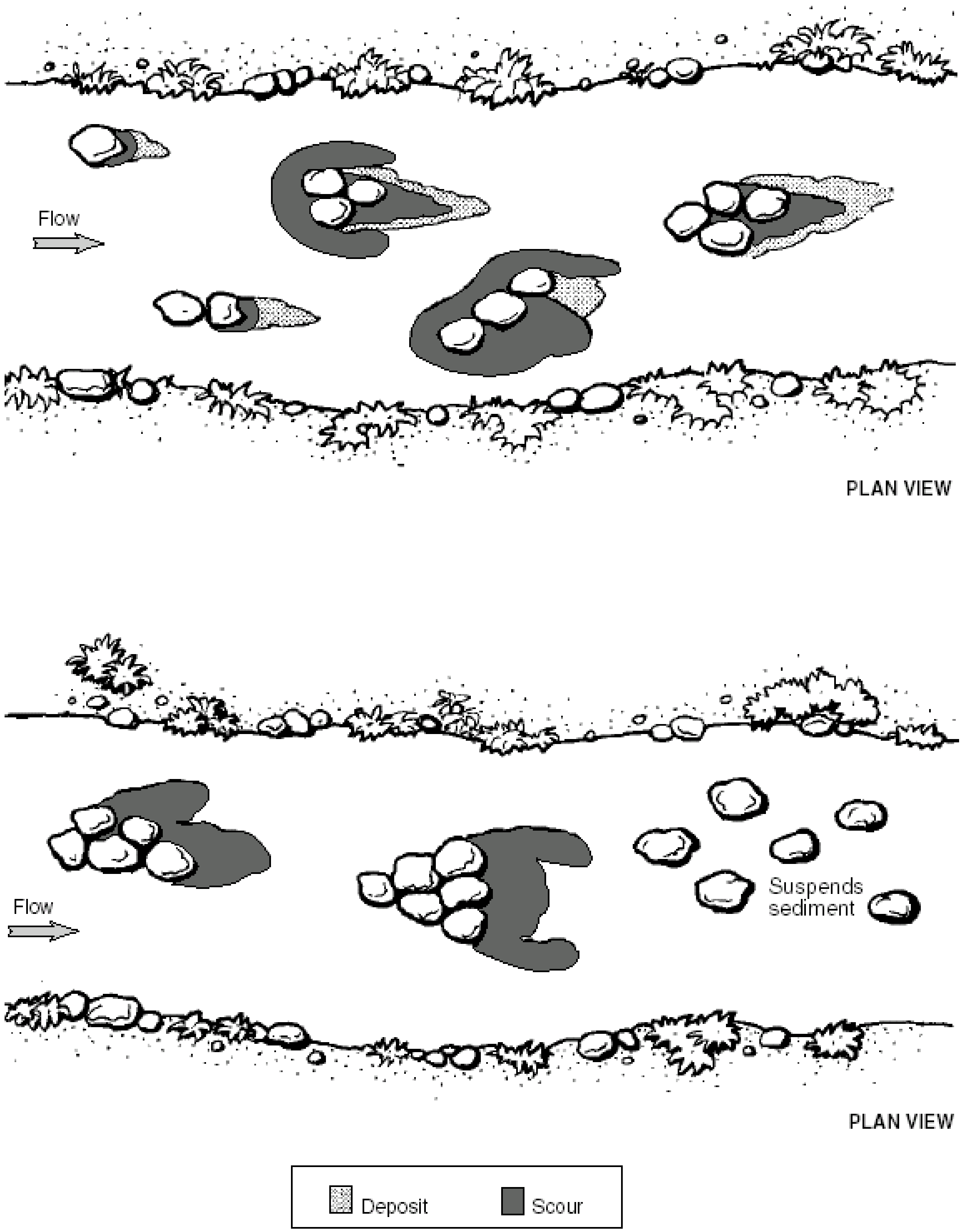
Clusters typically consist of three to seven boulders that are spaced 6 inches to 3 feet apart, the distance increasing with the size of the stream (see to **Boulder Cluster Figure 1***)*. Clusters should be located 10 to 12 feet apart[4 9] to allow passage of bed material and floating wood and limit the reduction in streamflow capacity. Bearing this in mind, boulder clusters should be arranged to compliment each other and work together to direct flow into areas where scour is desired (particularly at bankfull discharge) and away from those where it is not (e.g., an eroding bank supporting critical infrastructure). Boulder clusters should guide flow into and through natural channel meander bends. For example, boulders could be placed to accelerate flow into a natural bend to deepen the scour pool during bankfull stage. The next set of boulders downstream should then complement the upstream locations by being far enough downstream to prevent a backwater that would reduce the upstream scour objectives and be in line with the natural stream thalweg coming out of the upstream bend. Where flow redirection is the primary project objective of boulder placement, porous weirs may offer a complementary or alternate technique to boulder clusters. Further details on their application and design are provided in the technique titled *Porous Weirs*.


Concentrate boulder clusters in the thalweg to maximize habitat during low flows.
Edge of bankfull channel
Boulders should not occupy over 20–30% of the bankfull channel cross-section unless the channel is extremely stable. Adjacent boulder clusters should be spaced at least 10 ft. apart.
Downstream "V"
Upstream "V"
NOT TO SCALE
STREAM HABITAT RESTORATION GUIDELINES
http://www.wa.gov/wdfw/hab/ahg/shrgdoc.htm
BOULDER CLUSTERS CONCEPTUAL DESIGN
FIGURE 1

Boulders divide and redirect streamflow around them. The pattern of scour and deposition around boulders is related to the hydraulic action of the site during bankfull discharge. It is a function of the shape of the rock and its orientation relative to that of flow (see **Boulder Clusters Figures 2 and 3**). Rocks and rock clusters with a blunt upstream face placed perpendicular to flow cause an abrupt redirection of flow and create horseshoe-shaped scour around them, the deepest scour occurring at their upstream face. Rocks placed in this orientation are more likely to undermine and tip into their scour holes and to direct flow into nearby banks. They are also prone to being rotated by flow and point flow in a new direction. As a result, Johnson and Stypula recommend that, when using elongated rocks, they be installed with the long axis parallel or at a slight angle to flow, as they will be more stable.



Boulder Cluster Figure 2: Flow redirection as a result of boulder placement.



Boulder Cluster Figure 3: Typical patterns of scour and deposition associated with boulder clusters. Reprinted with permission from Johnson and Stypula (1993).

As scour pools develop in the vicinity of boulders, boulders will likely sink or tip into them unless they are embedded into the streambed to the maximum depth of scour during construction. Rock may be embedded by either digging a receiving hole or by wiggling or pushing the rock into the bed with an excavator. Being embedded should increase the rock's resistance to shear stress. Where movement or rotation of boulders following placement will be unacceptable, embedding the rocks so that their lower edge is at or below the anticipated depth of scour is highly recommended and will lower the risk of unintended consequences caused by rock rotation or by the rock sinking further or not as far as expected. Rocks that sink deeper than expected may become completely buried or protrude very shallowly into flow and provide less habitat benefits than desired. Rocks that remain higher than expected will have a bigger impact on channel hydraulics and debris collection than planned. As cited by Johnson and Orsborn, Cullen[11] found that the depth and extent of scour in the vicinity of boulders increases little with increasing flow once the boulders are completely submerged (once submerged, boulders obstruct a decreasing percentage of the total flow area as flow continues to rise). All else being equal, lower amounts of scour will be generated as the height of rock protrusion into bankfull flow declines.

Designers are encouraged to visit and review earlier boulder projects and natural analogs to familiarize themselves with habitat characteristics resulting from various placement strategies, particularly within the stream in question. Ideally, the size and shape of the boulders, their arrangement and their orientation, should all be based on the watershed hydrology and the hydraulic conditions at the candidate reach. In reaches lacking any natural analogs, detailed scour evaluation should be conducted as part of design. For further discussion of scour and the computation of scour, refer to the *Hydraulics* appendix. If possible, in high-risk situations it may be prudent to proceed stepwise in placement giving each placement time to have its effect before going so far as to cause undesirable results.

5.3 Boulder Materials

Generally, minimum boulder size is of greater concern than maximum boulder size. Boulders that are too small will wash away, or simply fall into scour holes and become buried or ineffective. Boulders should be sized to be immobile at the design flow, and large enough that they will not fall into scour holes and become buried. Considering the cost of completing habitat projects, it is recommended that boulders be sized withstand the shear stress or tractive force generated during the 50-year flow at a minimum, and ideally for the 100-year flow. Lower design flows are acceptable, but there is little reason for such rock forms to be deformable and, therefore, little harm in erring on side of conservative design flows to minimize risks and ensure long-term value. Also, the cost of larger boulders may be inconsequential when looking at total project costs. Any debris caught on boulders magnifies the total shear stress imposed on the boulders substantially during large floods. If these torques and additional forces are not estimated directly and accounted for, the 100-year design flow provides some degree of protection against these additional forces during lesser (20 to 50 year) storm events. The risk of boulder movement increases with channel gradient, water depth, degree of channel confinement, and the likelihood of wood impacting or collecting against them. Material sizing guidance given in the *Drop Structure* technique also applies to boulder clusters. Calculated rock sizes should be verified against the size of boulders that are naturally maintained in the stream.

In general, the designer should strive to use natural materials as much as possible, and to use materials appropriate to the location and stream type. Rock used in porous weirs should be sound, dense, and free from cracks, seams and other defects that would tend to increase its deterioration from weathering, freezing and thawing, or other natural causes. Angular and irregular shaped boulders (e.g., quarried rock) typically provide greater hydraulic complexity and cover than rounded boulders. Angular rock is also less likely to roll[12] and, therefore, offers greater resistance to shear. Most rock-sizing equations and methods are based on angular, durable rock. The diameter of rounded rock, if used, will have to be greater than the mean dimension of angular rock to provide the same resistance to entrainment. While angular rock may offer some advantages for stability and habitat, the use of angular boulders can have significant aesthetic impact, particularly in systems that are dominated by rounded rock.

6 PERMITTING

As boulder placement involves in-channel work and the placement of fill within the channel, required permits and checklists may include, but are not limited to, State Environmental Policy Act (SEPA) and a Joint Aquatic Resource Permits Application (JARPA) (including a Hydraulic Project Approval and possibly a Shoreline Management Act Permit, Section 401 Certification, and Section 404 Permit). An Endangered Species Act Section 7 or 10 Consultation or a Washington Department of Natural Resources Use Authorization may also be required. Refer to the *Typical Permits Required for Work in and Around Water* appendix for more information regarding each of these permits and checklists, and other permits that may apply.

7 CONSTRUCTION CONSIDERATIONS

Compared to other in-channel construction, the installation of boulder clusters will have low to moderate impacts on the stream with regards to increased turbidity and rearranging of bed and bank material. The greatest in-stream impacts are associated with digging receiving holes for the boulders within the channel. General construction considerations relevant to all in-channel work, and ways to reduce them, are detailed in the *Construction Considerations* appendix. Principle construction issues relevant to boulder placements include locating, transporting and installing boulders. Permit restrictions may require that additional factors be considered.

Installation of boulder clusters requires careful placement of rock. Rock should never be dumped into the stream. A hydraulic excavator with a bucket and thumb attachment that can comfortably move the boulders for a project is a good choice. Front-end wheeled loaders and track loaders can move boulders but have a limited ability to accurately place them. Clam shell buckets or grapple loader attachments on track machines have a greater degree of refinement or ability to place material exactly where needed but they are limited in their digging ability and strength. Therefore, in most projects an excavator with a thumb is the best all around ground based machine for boulder placement, provided that there are many available access points to the site and the excavator can easily move up and down the stream channel. A long arm excavator (60 feet reach) may be needed to reach over vegetation and put the rock out in the stream channel. However, long reach excavators are limited in their weight lifting capabilities and should only be considered for smaller boulders (less than 2 foot diameter) on smaller streams. Helicopters have been used to place boulders in remote sites that can’t be accessed by heavy equipment. Boulder weight will determine the type of helicopter needed to move the boulders.

Note that motorized wheel barrows, rock bars, winches, and other hand tools may be required where heavy equipment access is limited and to fine-tune boulder placement.

It is possible to work in water if precautions are taken. In many cases boulder placements are very unobtrusive and only require an excavator to walk the boulder to the location and place it. This type of project will produce very little sediment and can be very feasible when implemented during appropriate in-water work windows. It is recommended that fish be removed and excluded from the work area and that hydraulic fluid in heavy equipment be replaced with biodegradable fluid (e.g., vegetable oil) when working in or near moving water.

Except under special circumstances, construction equipment used for placement will not be permitted to operate in flowing water due to the potential impacts to in-stream habitat and biota. The project site will need to be dewatered or else equipment will be restricted to the bank where riparian vegetation will be trampled or removed. Depending on the condition of the riparian zone, the later may or may not be acceptable. Dewatering (discussed in the *Construction Considerations* appendix) facilitates installation, prevents siltation of the stream during construction, and minimizes trampling of habitat and aquatic life.

In addition to in-stream habitat, consideration should be given to the potential riparian habitat impacts to access and staging areas for construction. These areas will probably experience short-term impacts and will require reclamation and revegetation. The number and location of access points must be selected to minimize damage to the existing riparian vegetation. At project completion, disturbed areas, including staging and access areas, will need to be graded smooth, seeded, and planted to repair damage and restore the riparian zone.

Construction should be conducted during a period where impacts to critical life stages of fish and wildlife are avoided. Low-flow conditions are ideal for the placement of boulders and may be essential in situations where dewatering is required. Allowable in-stream work windows vary among fish species, other aquatic organisms, and streams. Contact the Washington Department of Fish and Wildlife's Area Habitat Biologist for information on work windows.

Boulder placement techniques can be conducted either as time and materials contracts or as unit cost contracts (per boulder placed). Unit cost contracts may be most appropriate when using experienced contractors and when placements have been thoroughly planned. Time and materials contracts are more appropriate when considerable uncertainty exists with regards to access and when fit-in-field placement is anticipated.

8 COST ESTIMATION

The costs associated with boulder placement depend on the availability of boulders, proximity of the material source to the site, available access to the site, and the type of equipment used. Access to the stream may be limited to certain locations. As a result, boulders are often delivered to access points and stockpiled. The cost to deliver boulders to the stockpile locations is estimated to be between $35 and $300 per boulder (based on a 3-ft diameter rock).

A hydraulic excavator (with operator) will cost $100 to $150 per hour. With this type of equipment, a laborer ($35 per hour) and a construction supervisor / site engineer ($65 per hour) would be required. The total hourly cost would therefore be about $200 to $250 per hour. Assuming access conditions do not limit progress rates, an average of four boulders could be placed per hour. The average cost for placing each boulder is therefore estimated to be about $50 to $65.

A small helicopter (with pilot) will cost about $1,200 per hour. With this type of equipment, two laborers (one at the stockpile and one at the placement location) and a site engineer would be required. The total hourly cost is therefore estimated to be about $1,335. It is estimated that an average of 10 boulders could be placed per hour. With this method, the average cost for placing each boulder is therefore estimated to be about $135.

The total cost for delivering a boulder to the stockpile and placing it in the river is therefore estimated to range from $85 to $400, depending on whether a hydraulic excavator or a helicopter is used. In some portions of the river, it might be feasible to operate the hydraulic excavator while other portions of the river might require the use of a helicopter.

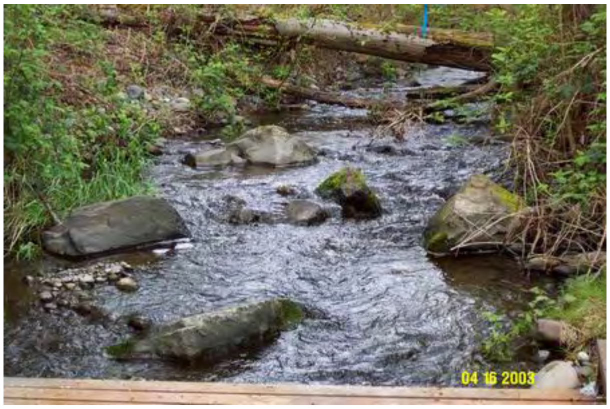
9 MONITORING

Monitoring methods employed depend on your objectives. Potential questions include: Did the boulders stay in place? Is maintenance required? Did the treatment affect overall fish production in the system? How has the habitat changed since the addition of the boulders? Does the structure provide favorable fish habitat (what fish, season, and age class)? The level and frequency of monitoring required will vary with monitoring objectives and project risk. Low risk projects may simply warrant annual site visits and a documentation of qualitative observations regarding scour, deposition, fish use, and boulder stability. On the other hand, projects that pose a relatively high risk to infrastructure, property, or habitat may require frequent quantitative physical and biological surveys to be conducted. Such surveys may include photos and detailed pre- and post-construction surveys of boulder locations and bed and bank topography to document changes over time, pre- and post-construction snorkeling of the site and a reference reach to document fish use. Refer to the *Monitoring Considerations* appendix for guidance on developing and implementing a monitoring plan.

10 MAINTENANCE

Regular monitoring of the site after high flow events will identify any maintenance requirements. Maintenance of a boulder placement project should not be required except in a few situations where the project is no longer meeting its objectives or unintended consequences have occurred and are unacceptable. Maintenance, when needed, may include re-positioning or removal of individual boulders, removal of wood that has racked up against the boulders, or armoring of eroding banks. However, keep in mind that repositioning of boulders is only recommended after careful evaluation to determine what went wrong to avoid repeating the mistake.

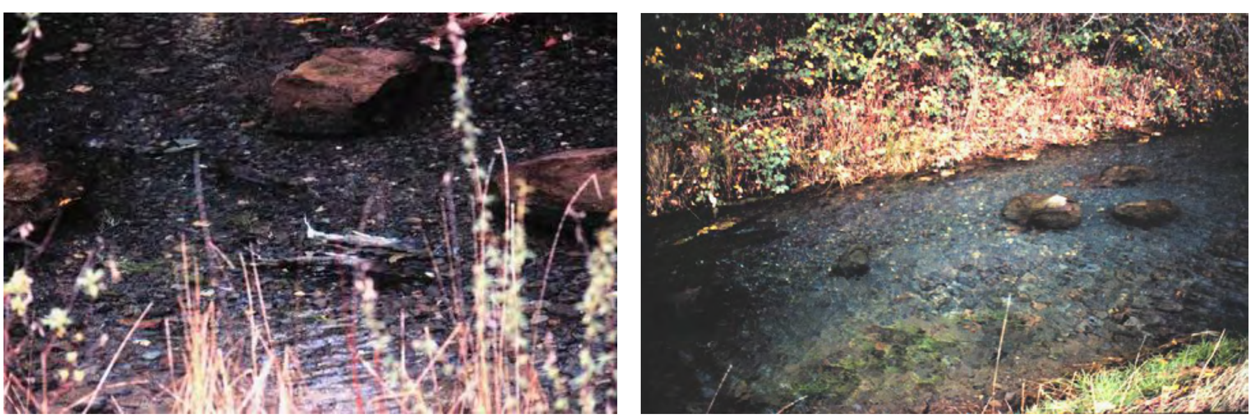
11 EXAMPLES



Boulder Clusters Figure 4: Constructed boulder clusters in Hylebos Creek, King County, Washington

Boulder Clusters Figure 5: Constructed boulder clusters in Lynch Creek, King County, Washington

Boulder Clusters Figure 6: Constructed boulder cluster in Touchet River, Columbia County, Washington



Boulder Clusters Figure 7: Constructed boulder cluster in Hamilton Springs, Skamania County, Washington. Note the presence of chum salmon in the photo on the left.

(a) **(b)**

Boulder Clusters Figure 8: Constructed boulder cluster during **(a)** low and **(b)** high flows in the Washougal River, Clark County, Washington. Photo provided courtesy of the Lower Columbia Salmon Enhancement Group.

Boulder Clusters Figure 9: Constructed boulder clusters in the Tucannon River, Columbia County, Washington.

Boulder Clusters Figure 10: Constructed boulder clusters in unknown stream.

Boulder Clusters Figure 11: Constructed boulder clusters in Murderers Creek.

12 GLOSSARY

Plane bed – a streambed characterized by a planar, formless surface
Shear stress – The force exerted on the bed and banks of the channel by moving water. Shear stress is a function of the slope of the water surface and the hydraulic radius of the channel (cross-sectional area divided by the cross–sectional length of the wetted channel). In very wide shallow channels, the hydraulic radius approximates the depth of flow.

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