Technical Supplement 14J

Use of Large Woody Material for Habitat and Bank Protection

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Cover photos: *Top*—Logs and rootwads may be designed to protect eroding streambanks.

Bottom—Large woody material is an important ecological component of many streams in the United States.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

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The Use of Large Woody Material for Habitat and Bank Protection

Introduction

Large woody materials (LWM) have been used for river training and stabilization for centuries. Many of the earliest river training structures built on large rivers in the United States included willow mattresses, brush mattresses, or wooden pilings driven into the bed. More recent efforts include tree revetments and other structures featuring large wood that were placed in the Winooski River, Vermont, in the 1930s, as part of a successful comprehensive watershed stabilization project (Edminster, Atkinson, and McIntyre 1949; U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) 1999a). A wide-ranging federally funded streambank protection research and demonstration program in the 1970s included several field trials of LWM-based protection schemes (U.S. Army Corps of Engineers (USACE) 1981). Most of these installations produced favorable short-term results for erosion control and in terms of costs, although some projects were damaged by ice (Henderson 1986).

In the 1970s, George Palmiter developed a suite of techniques involving repositioning LWM for controlling erosion and high-frequency flooding along low-gradient, medium-sized rivers clogged with debris and sediment. His approach featured use of hand tools and small power equipment (Institute of Environmental Sciences, Miami University, 1982; National Research Council 1992). A 1986 evaluation of 137 log habitat structures in the Northwest revealed high rates of damage and failure (Frissell and Nawa 1992).

During the 1990s, increasing appreciation of the importance of large wood in natural riverine ecosystems triggered efforts to design structures that emulated the form and function of naturally occurring, stable accumulations of wood, particularly in rivers of the Pacific Northwest (Abbe, Montgomery, and Petroff 1997; Hilderbrand et al. 1998). However, rootwad composites, which are currently among the most popular types of large wood structures, do not resemble any commonly observed large wood formations.

Area of applicability

LWM structures are intended to provide habitat and stabilization until woody riparian vegetation and stable bank slopes can be established. LWM decays within a few years unless it is continuously submerged. Therefore, structures made entirely or partially of woody materials are not suited for long-term stabilization unless wood is preserved by continuous wetting or with chemicals. Woody structures are best applied to channels that are at least moderately stable, have gravel or with finer bed material, and need wood for habitat. More detailed criteria are summarized in table TS14J–1 (adapted from Fischenich and Morrow 2000).

Woody material structures, like most bank protection, are not suited for reaches with active bed degradation. Streams not transporting sediments or steep, high-energy systems transporting large cobbles and boulders are usually not good candidates for woody material structures. Although there are many examples of woody material projects, the basis for design is somewhat limited by a lack of quantitative data for design, performance, and environmental effects. Furthermore, many of the most important design variables are regional or site specific. An overview of published values computed or assumed for key design variables is provided in table TS14J–2. This table is intended to provide an impression of the limitations of current design criteria, and suggested design values are presented. Long-term performance information is limited (Thompson 2002; USDA NRCS 1999a). Accordingly, wood structures are not well suited for high-hazard, high-risk projects.

Environmental and habitat considerations

Although early interest in the use of wood structures for stream stabilization was driven by the need for low-cost approaches, current understanding includes consideration of the important role that woody materials play in creating and providing the diverse conditions typical of aquatic habitats (Gurnell et al. 2002). Knowledge regarding geomorphic and ecological functions of wood in rivers is rapidly increasing. Considerable evidence suggests that streams across North America were dominated by inputs and large accumulations of woody materials prior to European settlement (fig. TS14J–1).

Table TS14J–1 Limitations on applicability of large wood structures

Variable	Considerations
Habitat requirements	Provides physical diversity, cover, velocity shelter, substrate sorting, pool development, undercut banks, and sites for terrestrial plant colonization using natural materials
Existing LWM density	Absent or depressed relative to similar nearby reaches that are lightly degraded
Sediment load	Generally not suitable for high-energy streams actively transporting material larger than gravel. LWM structures may be rapidly buried in high sediment load reaches, diminishing their aquatic habitat value, but accelerating recovery of terrestrial riparian habitats
Bed material	Anchoring will be difficult in hard beds such as cobble, boulder, or bedrock
Bed stability	Not suitable for avulsing, degrading, or incising channels. The best situations include areas of general or local sediment deposition along reaches that are stable or gradually aggrading. Deposition induced by LWM structures may be stabilized by planted or volunteer woody vegetation, fully rehabilitating a naturally stable bank by the time the placed woody materials decay (Shields, Morin, and Cooper 2004). Unlike some of the other structures, rootwads often create scour zones, not deposition
Bank material	LWM structures placed in banks with >85% sand are subject to flanking
Bank erosion processes	Not recommended where the mechanism of failure is mass failure, subsurface entrainment, or channel avulsion. Best when toe erosion is the primary process
Flow velocity	Well-anchored structures have been successfully applied to situations with estimated velocities —2.5 m/s (D'Aoust and Millar 2000). Rootwad installations have withstood velocities of 2.7 to 3.7 m/s (Allen and Leech 1997). Engineered logjam (ELJ)-type structures withstood 1.2 m/s in a sand-bed stream (Shields, Morin, and Cooper 2004)
Site access	Heavy equipment access usually is needed to bring in and place large trees with rootwads
Conveyance	LWM structures can increase flow resistance if they occupy significant parts of the channel prism (Shields and Gippel 1995; Fischenich 1996)
Navigation and recreation	LWM should not be located where they will pose a hazard or potential hazard to commercial or recreational navigation. Potential hazards are greatest for structures that span the channel
Raw materials	Suitable sources of trees needed nearby
Risk	Not suited for situations where failure would endanger human life or critical infrastructure

Table TS14J–2 Published values for design variables for LWM structures

Quantity	Used for	Typical values	Source
Density of wood in g/cm^3 (lowest, or worst-case condition[1/])	Buoyant force computation	0.4 to 0.5 0.5 0.4 to 0.5	Shields, Morin, and Cooper (2004) D'Aoust and Millar (2000) D'Aoust and Millar (1999)
Drag coefficient	Drag force computation	0.7 to 0.9 Up to 1.5 0.4 to 1.2 1.0 1.2 to 0.3 (tree) 1.2 (rootwad)	Shields and Gippel (1995) Alonso (2004) Gippel et al. (1996) Fischenich and Morrow (2000) D'Aoust and Millar (2000) D'Aoust and Millar (1999) D'Aoust and Millar (1999)
Design life for wood, yr	Planning	5 to 15	Fischenich and Morrow (2000)
Soil strength	Analysis of loads/ anchoring provided by buried members	Soil forces on buried members neglected in order to be conservative. Range of values based on soil types	Shields, Morin, and Cooper (2004)

1/ Worst case conditions presume well-dried wood. Dry wood rapidly absorbs water and may increase its density by 100% after only 24-hr submergence (Thevenet, Citterio, and Piegay 1998). However, critical conditions, especially along smaller streams, are likely to occur before wood has had time to fully absorb water.

Figure TS14J–1 Large historical logjams of LWM, Great Raft, Red River, LA

Native communities of plants and animals depend on habitats provided by wood. Large wood has been observed to support step-pool morphology, generate local scour and deposition, and even to create dams and trigger avulsions on streams of all sizes. Natural wood accumulations reduce flow-through velocity at baseflow (Shields and Smith 1992), facilitating retention of organic materials for processing by lower levels of the food web. Woody material is an important substrate for benthic macroinvertebrates (Wallace and Benke 1984) and provides diverse pool habitat, cover, and velocity refugia for fish and other animals. Visual cover from predators is important for fish in many stream ecosystems. Terrestrial and amphibious animals use instream wood for basking and perching. Riparian plants often rapidly establish on deposition associated with woody material. Habitat rehabilitation projects often feature addition of woody materials to streams, primarily for habitat reasons and only secondarily for erosion control or channel stabilization (Fischenich and Morrow 2000). Local effects of wood structures (whether they induce scour or deposition) depend on structure design and site variables.

Design

Design of woody material structures should follow a geomorphic and ecological assessment of the watershed and a similar, more detailed assessment of the reach or reaches to be treated including an analysis of existing conditions and anticipated responses related to stability, as well as habitat diversity. Site assessments are described in more detail in NEH654.03.

Types of LWM structures

Existing designs for large wood structures may be grouped into a few basic configurations, as shown in table TS14J–3. Only general concepts are presented, as numerous variations are found. Combinations of woody materials with stone and living plant materials are common. The first three types shown in table TS14J–3 are intermittent structures, while the last three provide continuous protection along an eroding bank. Rootwads may be placed at spaced intervals or in an interlocking fashion so they may be considered either intermittent or continuous types. The design and construction of rootwads and tree revetments are also addressed in NEH654 TSTS14I. Intermittent structures provide greater aquatic habitat diversity than continuous protection. Existing design criteria for engineered log jams (ELJ) were developed based on experience in wide, shallow, coarse-bed streams in the Pacific Northwest. Application of these concepts to streams with relatively deep channels, sand beds, and flashy hydrology requires considerable modification (Shields, Morin, and Cooper 2004). Figure TS14J–2 depicts LWM (also known as large woody debris) where it is an impediment to flow or navigation, as illustrated in figure TS14J–2. Woody materials have been shown to be an integral part of stream ecosystems. However, LWM such as this can also be used for restoration purposes.

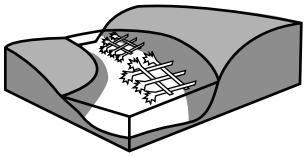
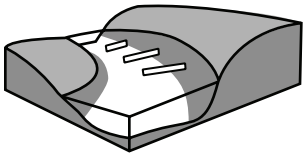
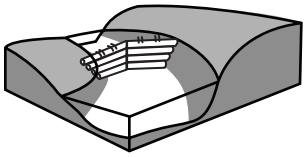
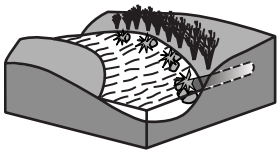
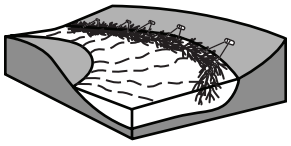
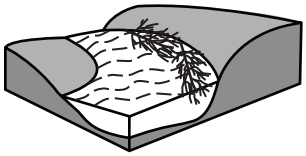
Selecting a type of structure

Configuration of a LWM structure should be selected using similar criteria that are employed for selecting any approach for stream stabilization or habitat rehabilitation:

- The configuration should address the dominant erosion processes operating on the site (Shields and Aziz 1992).
- Key habitat deficiencies (lack of pools, cover, woody substrate) should be addressed.

Figure TS14J–2 White River, IN, with large woody debris *(Photo courtesy of USGS)*

Table TS14J–3 Classification of large wood instream structures

Configuration	Sketch	Description	Strengths	References
Engineered logjams		Intermittent structures built by stacking whole trees and logs in crisscross arrangements	Emulates natural formations. Creates diverse physical conditions, traps additional debris	Abbe, Montgomery, and Petroff (1997); Shields, Morin, and Cooper (2004)
Log vanes		Single logs secured to bed protruding from bank and angled upstream. Also called log bendway weir	Low-cost, minimally intrusive	Derrick (1997); D'Aoust and Millar (2000)
Log weirs		Weirs spanning small streams comprised of one or more large logs	Creates pool habitat	Hilderbrand et al. 1998; Flosi et al. (1998)
Rootwads		Logs buried in bank with rootwads protruding into channel	Protects low banks, provides scour pools with woody cover	
Tree revetments or roughness logs		Whole trees placed along bank parallel to current. Trees are overlapped (shingled) and securely anchored	Deflects high flows and shear from outer banks; may induce sediment deposition and halt erosion	Cramer et al. (2002)
Toe logs		One or two rows of logs running parallel to current and secured to bank toe. Gravel fill may be placed immediately behind logs	Temporary toe protection	Cramer et al. (2002)

- The finished project should function in harmony with the anticipated future geomorphic response of the reach.
- Economic, political, institutional, and construction access issues should be considered.
- Suitable materials must be available for reasonable cost.
- Safety issues for recreational use of the completed project reach should be addressed, if appropriate.
- Structures like weirs or spurs that protrude into the flow tend to create greater habitat diversity than those that parallel banks, like revetments, with attendant effects on fish (Shields, Cooper, and Testa 1995).

Dimensions for intermittent LWM structures

The geometry of intermittent (spur-type) LWM structures may be specified by crest angle, length, elevation, and spacing. Spur-type structures are addressed in more detail in NEH654 TS14H.

The crest angle (angle between a line normal to the approach flow vector and the weir crest) may be set at 15 degrees upstream from a line drawn perpendicular to flow to promote deflection of overtopping flow away from eroding banks. Based on results of straight channel flume tests, Johnson, Hey, et al. (2001) suggested that stone spur-type structures be angled upstream so that the angle between the bank and the crest is between 25 degrees and 30 degrees. However, the angles can approach 90 degrees on straighter channels. Wood members embedded in the bank with their butts or rootwads pointing upstream may gain stability as drag forces tend to push them into the bank.

Crest length for structures that do not span the channel may be based on a projected value for the equilibrium width of the channel. Alternatively, crest length may be based on a target flow conveyance for the design cross section. A step-by-step procedure for spacing these structures is provided in NEH654 TS14H.

In incised channels, crest elevations for ELJ-type structures must be high enough so that the sediment berms that form over the structures stabilize existing near-vertical banks. Stable bank heights and angles may be based on geotechnical analyses or empirical criteria based on regional data sets. Castro and Sampson (2001) suggest crest elevation be set equal to that of the channel-forming flow stage. Conversely, Derrick (1997) suggests that even very low structures can exert important influence on flow patterns. All other factors being equal, local scour depths tend to be greater for higher structures.

Spacing between intermittent wood structures should be great enough to provide segments of unprotected bankline between structures to reduce cost and to create physical habitat diversity (Shields, Cooper, and Knight 1995), but also prevent flanking and structural failure. Spacing for intermittent structures is normally expressed as a multiple of the length of the structure from bank to riverward tip, measured perpendicular to the approach flow (projected crest length or effective length). Sylte and Fischenich (2000) suggest that spacing be three to four times the projected crest length for bends with $R_c/W > 3$ (radius of curvature/bankfull width), decreasing to 0 for $R_c/W < 2.5$. Tortuous channels can be problematic. Shields, Morin, and Cooper (2004) suggested that ELJ-type structures should be spaced one and a half to two times the crest length apart, following criteria for traditional training structures presented by Petersen (1986).

The embedment length or dimension for bank key-in for structures that are partially buried in the bank varies with bank height, soil type, and stream size. The key-in should be sufficient to maintain the position of the rest of the structure throughout its design life and should be greater for frequently overtopped and highly erodible banks (Sylte and Fischenich 2000).

Force and moment analysis

Some workers have developed engineering design procedures for wood structures that considered all of the important forces acting during design events, thus allowing design of anchoring systems that produced given factors of safety (Abbe, Montgomery, and Petroff 1997; D'Aoust and Millar 2000; Shields, Morin, and Cooper 2004). Forces that may be considered in such an analysis include buoyancy, friction between the woody structure and the bed, fluid drag and lift, and geotechnical forces on buried members. Simplified approaches with inherent assumptions are available, including one in NEH654 TS14E.

Buoyant force—The buoyant force is equal to the weight of the displaced water volume. The net buoyant force, $\vec{F}_b$, is equal to the difference between the weight of the structure and the weight of displaced water:

$$\vec{F}_b = \left[\rho_{wood} V_{wood} - \rho_{water} V_{water}\right]\vec{g} \qquad \text{(eq. TS14J–1)}$$

where:
ρ = density
V = volume
$\vec{g}$ = the gravitational acceleration vector in the vertical direction

For a fully submerged structure,

$$V_{wood} = V_{water} = V \text{ and } \vec{F}_b = \left(\rho_{wood} - \rho_{water}\right)V\vec{g} \qquad \text{(eq. TS14J–2)}$$

Wood structures may have complex geometries, which makes determination of volume difficult, particularly for partially submerged structures. Computations may be simplified by assuming that logs are cylinders or cones, adopting advantageous coordinate systems, and treating rootwads and boles as separate elements (Braudrick and Grant 2000; Shields, Morin, and Cooper 2004). Alternatively, a volume computed from the outside dimensions of the structure may be multiplied by a porosity factor to allow for air spaces. Thevenet, Citterio, and Piegay (1998) suggested that this factor is 10 percent for wood jams and 7 percent for shrubs.

If the wood structure may be approximated by a triangular prism of height, h, and with a uniform specific weight $\gamma_{structure}$, a simple solution for the depth, d_{wn}, at which the structure becomes neutrally buoyant (buoyant forces =gravitational forces) may be computed using:

$$\frac{\gamma_{structure}}{\gamma_w} = \frac{d_{wn}}{h}\left(2 - \frac{d_{wn}}{h}\right) \qquad \text{(eq. TS14J–3)}$$

where:
γ_w = specific weight of water

Friction—The movement of large wood structures by sliding along the bed will be resisted by a frictional force, $\vec{F}_f$, with magnitude equal to the normal force, $\vec{F}_n$, times the coefficient of friction between the woody material and the bed.

$$\vec{F}_f = \mu_{bed}\vec{F}_n \qquad \text{(eq. TS14J–4)}$$

In the absence of measured data, Castro and Sampson (2001) assumed that $\mu_{bed} = \tan\theta$, where θ is the friction angle for the bed sediments. However, it should be noted that the normal force, $\vec{F}_n$, approaches zero as depth increases and the structure approaches neutral buoyancy. Therefore, $\vec{F}_f$ may be effectively zero for design conditions.

Drag—The drag force on an LWM structure may be computed using the equation

$$\vec{F}_d = \frac{C_D A \gamma_w \left[\vec{U}_o \times \vec{U}_o\right]}{2g}\vec{c} \qquad \text{(eq. TS14J–5)}$$

where:
$\vec{F}_d$ = drag force
C_D = drag coefficient
A = area of structure projected in the plane perpendicular to flow
$\vec{U}_o$ = approach flow velocity in the absence of the structure
$\vec{c}$ = unit vector in the approach flow direction

A woody material structure may be treated as a single body, rather than as a collection of individual cylinders (Gippel et al. 1996). For structures located on the outside of bends, the cross-sectional mean velocity should be increased by a factor of 1.5 to allow for higher velocities on the outside of bends (USACE 1991b). Drag coefficients may be computed using an empirical formula (Shields and Gippel 1995), and typically range from ~0.7 to 0.9 (table TS14J–2). Drag coefficients for cylinders placed perpendicular to the flow reach values as high as 1.5 for cylinders that are barely submerged due to forces associated with the formation of standing waves (Alonso 2004). Drag coefficients for geometrically complex objects like LWM structures vary less with angle of orientation to the flow than for simple cylinders and tend to fall in the range of 0.6 to 0.7 (Gippel et al. 1996). Alonso (2004) fit the following regression formulas to laboratory data and suggested that it might be used to compute the drag coefficient, C_D:

$$C_D = W \times \left[1 - 0.35\exp\left(\frac{-4G}{d}\right)\right] \times \left[1.062 + 2\times10^{-6}R_e - 3\times10^{-12}R_e^2 + 2\times10^{-18}R_e^3\right] \qquad \text{(eq. TS14J–6)}$$

where:
G = distance from the bottom of the log to the bed
R_e = cylinder Reynolds number, $\frac{Ud}{\nu}$

where:
U = magnitude of the approach flow velocity
d = diameter of the log
ν = kinematic viscosity of the water
W = factor to account for the increase in drag due to surface waves, and may be given by

$$W = -0.28 \ln\left[\frac{z}{d}\right] + 1.4 \qquad \text{(eq. TS14J–7)}$$

when z/d < 4, and W = 1 when z/d > 4,

where:
z = distance from the log centerline to the water surface

Drag forces are expected to rapidly diminish with time during the first few high-flow events as patterns of scour and deposition reshape the local topography (Wallerstein et al. 2001).

Lift—The lift force, $\vec{F}_L$, on an LWM structure may be computed using the equation

$$\vec{F}_L = \frac{C_L A \gamma_w \left[\vec{U}_o \times \vec{U}_o\right]}{2g} \vec{e} \qquad \text{(eq. TS14J–8)}$$

where:
C_L = lift coefficient
$\vec{e}$ = unit vector normal to the plane containing primary flow direction, $\vec{c}$, and the transverse axis of the structure

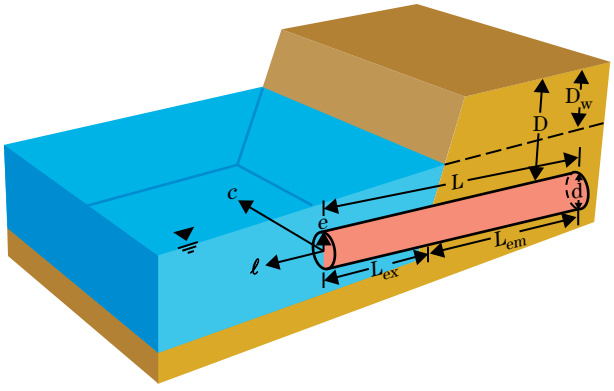
The lift coefficient on a single cylinder placed perpendicular to the flow is greatest (~0.45) when the cylinder is in contact with the bed and declines to near zero when the gap between the bottom of the cylinder and the bed exceeds one half times the cylinder diameter (Alonso 2004). As with drag, lift forces likely rapidly diminish as patterns of scour and deposition reshape the local topography (Wallerstein et al. 2001). Except for rare situations, lift may be neglected in design of LWM structures.

Geotechnical forces—The resistive forces due to passive soil pressure acting on buried portions of logs are direct reactions to fluid forces. A simplified analysis is presented here. A more detailed treatment that includes sloping banks and a nonhorizontal water table is presented by Wood and Jarrett (2004) and provides the basis for an associated Excel® worksheet. The following equations (Gray 2003) assume that the:

- log is embedded horizontally in the streambank
- top of the bank is horizontal
- bank is composed of homogeneous, isotropic soil with specific weight γ_{soil}, friction angle ϕ and cohesion c
- ground water table elevation in the bank is approximately equal to the stream surface elevation, which is high enough to fully submerge the log (fig. TS14J–3)
- bank slope is assumed to be near vertical
- the log is assumed to be frictionless

The log has a length = L, diameter d, and is buried a distance D below the top bank and a horizontal depth L_{em} (embedment length). The passive soil resistance distribution is assumed to be triangular with its maximum value at the bank face and decreasing linearly to zero at the embedded tip of the log. This implies that the resultant passive resistance force acts on the log a distance of $2/3L_{em}$ from the embedded tip. The active earth pressure force is assumed to be small, relative to the passive force.

Figure TS14J–3 Definition sketch for geotechnical forces on buried log



The vertical loading on the log due to the weight of the soil above it will be given by:

$$F_{soil} = \sigma'_v L_{em} d \qquad \text{(eq. TS14J–9)}$$

where:

$$\sigma'_v = \left(D - D_w\right)\left(\gamma_{soil} - \gamma_{water}\right) + D_w \gamma_{soil} \qquad \text{(eq. TS14J–10)}$$

where:

γ_{soil} = moist or total unit weight of the soil above the log

Alternatively, F_{soil} may be computed using equations developed to compute soil loading on conduits buried in ditches. When the ditch width is no greater than three times the log diameter,

$$F_{soil} = C_d \sigma'_v B_d^2 \frac{L}{D} \qquad \text{(eq. TS14J–11)}$$

where:

B_d = width of the ditch

C_d = a coefficient that captures the interaction between the ditch walls and the fill

$$C_d = \frac{\left[1 - e^{\frac{-0.38D}{B_d}}\right]}{0.38} \qquad \text{(eq. TS14J–12)}$$

$$\text{for } \frac{D}{B_d} < 2 \text{ and} \qquad \text{(eq. TS14J–13)}$$

$$C_d = \frac{D}{B_d} \qquad \text{(eq. TS14J–14)}$$

$$\text{for } \frac{D}{B_d} \geq 2 \qquad \text{(eq. TS14J–15)}$$

The two approaches for computing F_{soil} converge for ditches with widths just slightly greater than the log diameter.

Assuming friction between the soil and log is negligible, the passive soil pressure force, $\vec{F}_p$, is given by

$$\vec{F}_p = 0.5 \sigma_p L_{em} d \qquad \text{(eq. TS14J–16)}$$

where:

σ_p = passive soil pressure

is given by

$$\sigma_p = \sigma'_v K_p + 2c\left(K_p\right)^{0.5} \qquad \text{(eq. TS14J–17)}$$

where:

K_p = coefficient of passive earth pressure

is given by

$$K_p = \tan^2\left(45 + \frac{\phi}{2}\right) \qquad \text{(eq. TS14J–18)}$$

If unknown, soil cohesion, c, may conservatively be assumed to equal 0. Riparian soils are often noncohesive, and cohesion in cohesive soils is effectively 0 when soils are saturated.

Moments—The driving moment, $\vec{M}_d$, about the buried tip of the embedded log is given by the vector sum

$$\vec{M}_d = \left[\left(\vec{F}_d + \vec{F}_L\right)\left(L_{em} + \frac{L_{ex}}{2}\right) + \vec{F}_b\left(\frac{L}{2}\right)\right] \times \vec{l} \qquad \text{(eq. TS14J–19)}$$

where $\vec{l}$ is the unit vector along the axis of the buried log and positive in the direction away from the buried tip and $L_{ex} = L - L_{em}$. The resisting moment, $\vec{M}_d$, will act opposite the driving moment and is given by the vector sum

$$\vec{M}_r = \left[\vec{F}_{soil}\left(\frac{1}{2}\right)L_{em} + \vec{F}_p\left(\frac{2}{3}\right)L_{em} + \vec{F}_c L_c\right] \times \vec{l} \qquad \text{(eq. TS14J–20)}$$

where $\vec{F}_c$ is the restraining force due to anchor cables or ballast, and L_c is the appropriate moment arm about the buried tip of the embedded log.

Ballast and anchoring

Forces and moments due to anchors may be added to the other forces acting on the LW structure to compute factors of safety. The factor of safety with respect to forces, F_{sf}, is the ratio of the magnitude of the resultant of the resisting forces to the magnitude of the resultant of the driving forces with separate factors of safety computed for the vertical (y) and horizontal (x, streamwise) directions.

$$F_{sf_y} = \frac{F_{soil_y} + F_{py} + F_{cy}}{F_b + F_L} \qquad \text{(eq. TS14J–21)}$$

$$F_{sf_y} = \frac{F_{soil_x} + F_{px} + F_{cx}}{F_D} \qquad \text{(eq. TS14J–22)}$$

M_r acts opposite M_d, and both vectors act along a horizontal axis through the embedded tip of the log. Therefore, the factor of safety with respect to moments, F_{sm}, is simply the ratio of their magnitudes:

$$F_{sm} = \frac{M_r}{M_d} \qquad \text{(eq. TS14J–23)}$$

Anchoring systems should be designed to achieve factors of safety greater than 2 due to the high level of uncertainty in computations for imposed forces. Anchoring approaches include placing ballast (soil, cobbles, boulders) on or within the structure, embedding part or all of the large wood in the bank or in a stone structure, and using cable, marine rope, or chain to secure the structure to boulders, soil anchors (NEH654 TS14E), stumps, trees, deadmen, or pilings (Cramer et al. 2002; Fischenich and Morrow 2000). When logs or woody elements are used as ballast, it is important for the designer to consider the implications of the wood rotting and becoming lighter. When boulders or bed material are used for ballast, buoyant, drag, and lift forces on the ballast rock must be considered in the force balance (D'Aoust and Millar 2000). An electronic spreadsheet may facilitate this calculation.

Logs in complex structures may be attached to one another or to boulders by drilling holes through the logs and pinning them together with steel rebar. Epoxy adhesive has also been used for attaching logs. Abbe, Montgomery, and Petroff (1997) favor an approach that may be termed passive anchoring (Cramer et al. 2002), in which the shape, weight, ballast, and placement of a structure are adequate to resist movement in events up to the design flow. Passively anchored structures may be comprised of wood members that are attached to one another, but not to external anchors. Passive anchoring is not recommended for high hazard situations, sites with vulnerable infrastructure downstream, or sites where structures will be frequently overtopped.

Materials

Minimum dimensions, species, and sources for woody materials should be specified during design. Cramer et al. (2002) suggest the following guidelines for size of trees and rootwads:

Dimension	Minimum size
Rootwad diameter	Bankfull discharge depth
Trunk diameter	0.5 × bankfull discharge depth
Tree length	0.25 × bankfull discharge width

Clearly, wood materials this large are not always available. Onsite sources are always most economical; importing large materials can be extremely costly. However, benefits to the stream ecosystem must be weighed against the impacts of clearing and grubbing on existing terrestrial habitat. Complex woody material structures that feature numerous branches and high stem density locally decrease flow velocity, inducing sediment deposition. Accordingly, materials should be selected that have numerous branches, being careful not to break or remove branches during construction. Clearing within the stream corridor should be avoided, but bar scalping may be advisable in certain cases to provide temporary relief of outer bank erosion in a sharp bend. Resulting woody materials (willow rootwads and stems) may be used in structures to trigger rapid revegetation.

Species that are decay resistant are preferred, such as eastern red cedar (*Juniperous virginiana*), western red cedar (*Thuja plicata*), coastal redwood (*Sequioa sempervirens*), Douglas-fir (*Pseudotsuga* spp.), or bald cypress (*Taxodium distichum*). Rapidly decaying species, such as cottonwood (*Populus* spp.), pines native to the Southeast (*Pinus echinata* and *Pinus taeda*), and alder (*Alnus* spp.), should be avoided. However, as noted, use of freshly cut or grubbed willow or cottonwood trees may be desirable for quick revegetation in structures that are partially buried. Comments on decay rates are provided in table TS14J–4.

Decay rates are climate dependent, due to the requirements of the fungi responsible for aerobic decomposition of wood. Rates increase with increasing temperature and precipitation. Scheffer (1971) developed the following index for comparing potential decay rates of aboveground wood structures in different climatic regions of the United States.

Table TS14J–4 Comparison of desirability of various tree species for stream structures

Species	Durability (assuming wetting and drying)	Source of information[1/]
Cottonwood (*Populus* spp.)	Poor	Johnson and Stypula (1993)
Alder (*Alnus* spp.)	Poor	Johnson and Stypula (1993)
Maple (*Acer* spp.)	Fair (will survive 5 to 10 yr)	Johnson and Stypula (1993)
Hemlock (*Tsuga* spp.)	Least durable of conifers	Johnson and Stypula (1993)
Sitka spruce (*Picea sitchensis*)	Excellent	Johnson and Stypula (1993)
Douglas-fir (*Pseudotsuga* spp.)	Excellent (will survive 25 to 60 yr) 32–56 yr	Johnson and Stypula 1993); Harmon et al. (1986)
Western red cedar (*Thuja plicata*)	Most desirable (will survive 50 to 100 yr)	Johnson and Stypula (1993)
Yellow-poplar (*Liriodendron tulipifer*a)	0.4 yr	Harmon et al. (1986)
Aspen (*P. tremuloides*)	5 yr	Harmon et al. (1986)
White fir (*A. concolor*)	4 yr	Harmon et al. (1986)
Norway spruce (*Picea abies*)	~30 yr	Kruys, Jonsson, and Stahl (2002)
Conifers (*P. sitchensis*, *T. heterophylla*, *P. menziesii*, *T. plicata*)	Half-life of ~20 yr	Hyatt and Naiman (2001)
Black locust, red mulberry, Osage orange, Pacific yew	Exceptionally high heartwood decay resistance	Simpson and TenWolde (1999)
Old growth baldcypress, catalpa, cedars, black cherry, chestnut, Arizona cypress, junipers, honeylocust, mesquite, old growth redwood, sassafras, black walnut	Resistant or very resistant to heartwood decay	Simpson and TenWolde (1999)
Young growth baldcypress, Douglas-fir, western larch, longleaf old growth pine, old growth slash pine, young growth redwood, tamarack, old growth eastern white pine	Moderately resistant to heartwood decay	Simpson and TenWolde (1999)
Red alder, ashes, aspens, beech, birches, buckeye, butternut, cottonwood, elms, basswood, true firs, hackberry, hemlocks, hickories, magnolia, maples, pines, spruces, sweetgum, sycamore, tanoak, willows, yellow-poplar	Slightly or nonresistant to heartwood decay	Simpson and TenWolde (1999)

1/ Information from Johnson and Stypula (1993) is qualitative and unsubstantiated. Evidently, these comments pertain to the region of King County, Washington. Harmon et al. (1986) provide a review of scientific literature dealing with decomposition rates of snags and logs in forest ecosystems. The times from Harmon et al. (1986) represent the time required for 20 percent decomposition (mineralization) of a log based on exponential decay constants obtained from the literature. Fragmentation of logs in streams due to mechanical abrasion would accelerate the decay process, as would more frequent wetting and drying. Kruys, Jonsson, and Stahl (2002) provide data on decay of fallen and standing dead trees in a forest in mid-northern Sweden. Hyatt and Naiman (2001) provide data on residence time of large wood in Queets River, Washington. Simpson and TenWolde (1999) provide data for evaluating wood products, not whole trees.

$$\text{Climate index} = \frac{\sum_{\text{Jan}}^{\text{Dec}}\left[(T-35)(D-3)\right]}{30} \qquad \text{(eq. TS14J–23)}$$

where:

T = mean monthly temperature (°F)

D = mean number of days in the month with 0.01 inch or more of precipitation

The summation represents the sum of products for all of the months of the year. The sum is divided by 30 to make the index fall between 0 and 100 for most of the United States. For example, Scheffer computed values of 82.5, 44.8, and 22.0 for Atlanta, Georgia; Des Moines, Iowa; and Casper, Wyoming, respectively. This implies that a wood structure would last about four times longer in a climate typical of Wyoming than one typical of Georgia, all other factors being equal.

Synthetic LWM for stream work is available commercially (Bolton et al. 1998). These products are engineered to compare favorably with natural materials in terms of durability or habitat value. However, they may be less effective in terms of habitat creation or more costly than natural materials. Cost comparisons should consider full project life cycles.

Cost

Costs for LWM structures are heavily influenced by site variables and material sources. Cramer et al. (2002) provide typical cost ranges for large wood of $500 to $750 per tree with rootwad and $200 to $300 per tree without rootwad. These figures include material, hauling to the site, excavation, spoilage, and installation. Additional cost information is summarized in table TS14J–5.

Maintenance

LWM structures should be viewed as temporary measures to trigger desirable natural changes in channels and banks. Accordingly, structures gradually degrade and break down. However, structures should be maintained until planted or invading woody plants have succeeded in establishing in the treated area. A relatively high level of maintenance is necessary if initial configurations are to be maintained for more than a few years. Annual low-water inspections are advisable, with particular attention to anchoring systems, decay status of woody materials, hazards to downstream infrastructure, and erosion patterns. Habitat monitoring may be qualitative, but field measurement of water depth, width, and velocity (Shields, Knight, Morin, and Blank 2003) is preferable. Photo documentation and cross-sectional and thalweg surveys are most helpful in detecting changes. Cramer et al. (2002) recommend additional inspections following any event that equals or exceeds the 1-year flow during the first 3 years following construction.

Table TS14J–5 Reported costs for stream stabilization and habitat enhancement structures

Year	Location	Protected bank length, m	Unit cost[1/], $/m	Comments	Source
1987	Nestucca River and Elk Creek, OR	1,960	24	119 woody debris structures using 99 mature conifers placed for habitat objectives, not stabilization	House and Crispin (1990)
1990–91	North Fork Porter Creek, WA	500	165	Five different log configurations anchored with cables and boulders for habitat purposes only	Cederholm et al. (1997)
1990–91	North Fork Porter Creek, WA	500	13	60 trees > 30 cm diameter cut felled into stream from banks and tethered to stumps with cable for habitat purposes only	Cederholm et al. (1997)
1994	Buffalo River, AR		66	Cedar tree revetments and willow rootwads planted in ditches. Two of 13 sites have not performed well	Personal communication, David Mott, National Park Service
1996	Cowlitz River, WA	430	47	Engineered logjams. Includes estimate for value of donated materials	Abbe, Montgomery, and Petroff (1997)
1996	Bayou Pierre, MS	240	117	Eight tree-trunk bendway weirs spaced 30 m apart. Weirs consisted of two to four trees per weir cabled to 0.15-m steel pipes driven into bed. Riprap-protected keys. Two structures failed, others have performed well	Personal communication, Larry Marcy, U.S. Fish and Wildlife Service
1988–97	Six urban gravel bed streams, Puget Sound, WA	2,960	493	Anchored and unanchored LWM added for flood control, sediment/erosion control and habitat enhancement	Larson, Booth, and Morley (2001)
1998	Various, MO		72 [2/]	Double row tree revetment installed using heavy equipment	Personal communication, Brian Todd, State of Missouri
1999	Bitterroot River, MT		80	Rootwads	Brown and Gray (1999)
2000	Little Topashaw Creek, MS	1,500	80	72 LWM structures in small, sand-bed stream. Unit cost = $95/m when willow planting is included	Shields, Morin, and Cooper (2004)
2000	Various		40–200	Rootwads	Sylte and Fischenich (2000)
2002	Various		40–80	Roughness trees	Cramer et al. (2002)
2002	Various, WA		70–200	Log toe	Cramer et al. (2002)
1995–2002	Various, PA		79–213 [3/]	Rootwads	Wood (2003)

1/ Costs are for the construction contract and do not include design and contract administration. Construction materials, mobilization, and profit are included.
2/ Upper end of range provided by original source
3/ An emergency project that included importing fill to replace a 10 m high bank cost $591/m