RIVER RESEARCH AND APPLICATIONS
River Res. Applic. **28**: 1477–1487 (2012)
Published online 6 June 2011 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/rra.1538

LARGE WOODY DEBRIS IN URBAN STREAM CHANNELS: REDEFINING THE PROBLEM

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ABSTRACT

Large woody debris (LWD) is an important ecological element in rivers and streams. Despite its importance, LWD is often removed from urban stream channels for flood control or road maintenance purposes, an approach with high economic and ecological costs and one that is largely unsuccessful. We propose an approach to conserve LWD in channels by modifying infrastructure (culverts and bridges) to allow LWD passage, maintaining aquatic habitat and reducing flooding and road maintenance costs. In Soquel Creek (California, USA), which has a history of LWD-related flooding, we compared long-term LWD management costs of historical, current and a LWD-passing approach whereby infrastructure is enlarged to accommodate LWD passage downstream. We estimated costs of infrastructure replacement, programmatic flood control (LWD removal), LWD-related flood damage and lost aquatic habitat. The amount of lost aquatic habitat was determined by comparing LWD loading (pieces m^{-1}) in Soquel Creek (0.007 pieces m^{-1}) to nearby unmanaged streams (0.054 to 0.106 pieces m^{-1}). Estimated costs of infrastructure able to pass LWD were nearly double that of historical costs but comparable to current costs. The LWD-passing approach was comparable to removal approaches in the short term (1 to 50 years) but much less in the long term (51 to 100 years), as expenditures in infrastructure replacement to accommodate LWD yielded reductions in flooding costs and habitat loss. Given the urgency to maintain and restore aquatic habitat, the proposed approach may be broadly applicable. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: large woody debris; environmental planning; river restoration; ecological process-based management; aquatic habitat; urban stream channels; salmonid habitat

Received 15 April 2011; Accepted 19 April 2011

INTRODUCTION

Logs, stumps and branches that fall into and are stored within rivers are important elements in aquatic ecology (Keller and Swanson, 1979; Gregory *et al.*, 1991). These pieces of large wood interact with flow to create complex channel features that provide essential habitats for salmonid species (Bjornn and Reiser, 1991; Fausch and Northcote, 1992; Crispin *et al.*, 1993), store allochthonous material integral to aquatic food webs (Bilby and Likens, 1980; Trotter, 1990) and enhance and speed riparian forest regeneration (Fetherston *et al.*, 1995; Abbe and Montgomery, 1996). Large woody debris (LWD) is the common term applied to large wood pieces, and although debris is a pejorative term suggesting trash or rubbish, we use it here to remain consistent with previous literature. LWD was formerly removed from river channels to recover marketable timber (Maser and Sedell, 1994), to remove navigational hazards (Marzolf, 1978; Erskine and Webb, 2003) and to eliminate perceived barriers to fish migration (Brown, 1974). The importance of LWD to aquatic habitat and biota has been increasingly recognized, with international research conferences (Wood in World Rivers Conferences in 2000 and 2006) and associated special issues in peer reviewed journals (Geomorphology in March 2003, Earth Surface Processes and Landforms in July 2007). In many rivers with important salmonid species present, management has shifted in response to this understanding.

Management of LWD has evolved in many rural and wilderness settings. Recent forest management plans include guidelines to maintain riparian forest density (number of trees per unit area) and buffer width and instream LWD abundance (FEMAT, 1993; Spence *et al.*, 1996). Across and within regions, management plans may suggest different LWD metrics, minimum size criteria and minimum target levels to distinguish and characterize adequate aquatic habitat (Fox and Bolton, 2007), but the plans consistently recognize the value of LWD to rivers and streams. However, water-borne LWD can be transported downstream during high flows and collect upstream of culverts and bridge pilings and piers, undermining and weakening structures (Diehl, 1997). These conflicts are usually greater in urban environments (Piégay and Landon, 1997), where the threat to infrastructure and public safety drives the common management responses: to remove LWD from the channel or to install debris racks to intercept LWD in transport (Bradley *et al.*, 2005) in efforts to increase channel conveyance. However, such actions

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often fail to prevent flooding, in part because of new input of LWD during floods (Young, 1991; Gippel, 1995; Dudley *et al.*, 1998).

Thus, LWD management in urban areas implicitly assumes LWD is a problem and needs to be removed, resulting in degradation of aquatic habitat. An alternative, more sustainable approach to manage LWD in urban systems is to recognize the value of LWD and redefine the problem as the inability of infrastructure to pass LWD through the system. With the problem thusly redefined, managers could modify infrastructure and accommodate the processes of LWD input, storage and transport through the channel network by preserving zones of LWD recruitment (forested hillslopes and riparian corridors) and areas of LWD storage (gravel bars and floodplains) and maintaining pathways of LWD transport (Piégay and Landon, 1997). By obviating the need to remove LWD from the channel, its important ecological functions would be retained.

The purpose of this paper is to describe historical, current and potential alternative management approaches to managing LWD in channels based on modifying infrastructure to pass LWD, drawing upon data for Soquel Creek, California. We first sampled in-channel LWD to characterize the sizes recruited from the basin and compared the sizes of LWD to the size of openings in bridges and culverts to identify potential restrictions on transport. We then compare the costs of modifying infrastructure to permit LWD passage to the costs of historical and current management practices (involving removal of LWD and habitat mitigation), costs related to flood damage (or flood control) and costs of lost habitat.

STUDY AREA

The Soquel Creek basin drains a 109-km^2 catchment in the California Coast Ranges, dropping from 900 m to debouch into Monterey Bay at Capitola (Figure 1). The basin is mostly underlain by erodible, fine-grained Tertiary marine sedimentary rocks with occasional outcrops of granitic basement and is geologically controlled by the San Andreas Fault, running across the basin divide, and the sub-parallel Zayante fault, 4 km to the southwest (Singer and Swanson, 1983; Balance Hydrologics, Inc., 2003).

The upper basin is forested with second-growth and old-growth coast redwood (*Sequoia sempervirens*) and douglas-fir (*Pseudotsuga menziesii*), with Pacific madrone (*Arbutus menziesii*), and various oaks (*Quercus* spp.) on dry, south-facing hillslopes. Riparian sycamore (*Platanus racemosa*), alder (*Alnus* spp.), cottonwood (*Populus* spp.), big leaf maple (*Acer macrophyllum*) and California bay (*Umbellularia californica*) occur along streambanks and floodplains (Greening Associates, 2003).

The climate is Mediterranean with cool, wet winters and warm, dry summers. Annual average rainfall ranges from 38 cm along the coast to 114 cm at the basin divide and falls mostly from November to April (Balance Hydrologics, Inc., 2003). Average discharge (1952 to 2009) is 1.2 m^3 s^{-1}, and the highest recorded peak flow was 447 m^3 s^{-1} (1955), as recorded at the gauge Soquel Creek at Soquel (US Geological Survey gauge # 11116000).

Landslides are common throughout the basin, resulting from a combination of weathered parent material, steep hillslopes, seismic activity and punctuated intense rainfall (Cooper-Clark and Associates, 1975; Singer and Swanson, 1983). The most common mass movements are debris flows that contribute large volumes of woody debris and sediment to stream channels. The basin is also dotted with large rotational landslides that begin at ridge tops and are activated by earthquakes, such as those in 1906 and 1989 (Manson and Sowma-Bawcom, 1992).

The East Branch of Soquel Creek drains 50 km^2 of the upper catchment, within Soquel Demonstration State Forest, which was established in 1990 to demonstrate forest management practices, promote public recreational uses and host research projects (Figure 1) (Cafferata and Poole, 1993). From 1870 to 1940, intensive clearcut harvesting removed most old-growth redwood and douglas-fir trees from the catchment (Poole, 1993). The forest today is a mixture of second-growth coast redwoods and mixed evergreens on the hillslopes and riparian hardwoods along streambanks and floodplains. Despite selective harvest of second-growth trees over the past 30 years, the forest has the largest and least managed stock of LWD in the basin. Thus, the LWD present in its channels would most closely reflect the size characteristics of LWD supplied from the basin and transported through the channel network, unlike the rest of the drainage network, which is largely private ownership and subject to LWD removal.

The middle Soquel Creek basin is occupied by a combination of residential uses, orchards, plant nurseries and horse stables. The lower portion is urbanized, with the town of Capitola at the stream mouth (into Monterey Bay) and the town of Soquel several kilometres upstream, which occupies 0.3 km^2 of floodplain adjacent to Soquel Creek (Figure 1). The creek overflows its banks at discharges greater than 170 m^3 s^{-1}, and the 100-year flood is projected to inundate most of downtown Soquel (Swanson, 1988). Here the creek is crossed by the Soquel Drive Bridge, which has a history of blocking water-borne LWD during high flows and creating logjams that diverted flood waters from the channel onto the adjacent floodplain. This has occurred eight times over the past 100 years, with the greatest damage occurring in 1955 and 1982 during the two largest floods of record, both of which inundated the town to depths of 1.5 m. Because of LWD-related flooding and associated damage,

DOI: 10.1002/rra

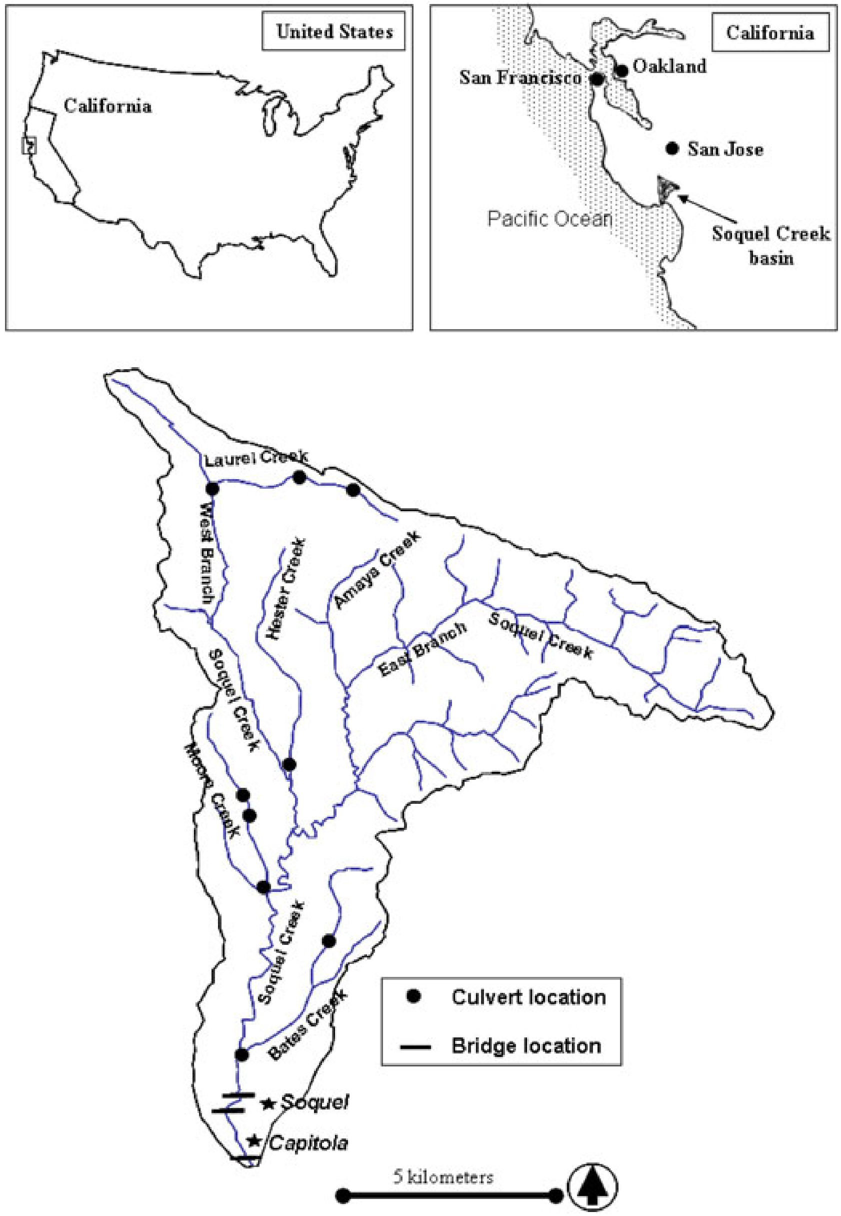

Figure 1. Location of Soquel Creek basin and location of culverts and bridges within the basin.

the Soquel Drive Bridge was replaced in 1890, 1927, 1956 and 2003 (Singer and Swanson, 1983; Lassettre, 2003).

In response to LWD-related flooding, the county of Santa Cruz initiated an instream wood management programme in 1971 to 'maintain the stream channels of the County free of debris, logs, and other materials that might be extremely hazardous to property during times of flood' (Santa Cruz County, 2009a). Under this programme, logs were manually removed, cut into small pieces to facilitate passage down the network or moved from the centre to channel margins to protect banks from erosion (Singer and Swanson, 1983). Despite these efforts, in which crews removed 'every stick of wood from Soquel Creek' (Santa Cruz County, 2009a), a massive logjam still formed at the Soquel Drive Bridge during the 1982 flood (Figure 2).

The wood management programme had not accounted for the temporal and spatial nature of LWD dynamics within the basin. Crews removed LWD during low flow, when conditions allowed access to the channel. But even if crews removed every last log from the channel, during a large storm and flood, there would be abundant LWD newly recruited to the channels from mass wasting, bank erosion and fluvial transport. By removing LWD, the programme degraded aquatic habitat, which was implicitly recognized by

DOI: 10.1002/rra

Figure 2. Logjam upstream of the Soquel Drive Bridge (Soquel, California, USA) after January 1982 storm. For scale, note oil drum (1 m height by 0.66 m width) entangled in logjam in upper left of photograph (photo taken by Gerald Webber, used with permission). This figure is available in colour online at wileyonlinelibrary.com/journal/rra.

a stream restoration programme intended to enhance habitat for federally endangered Coho salmon (*Oncorhynchus kisutch*) and federally threatened steelhead (*Oncorhynchus mykiss*). The programme used instream structures made of large wood to create channel complexity and habitat in the short term but did not restore the processes of LWD-related habitat creation. As a result, the structures required continued maintenance (Lassettre, 1997). Funding for the habitat restoration programme was discontinued in the late 1990s (Santa Cruz County, 2009a). The two programmes operated at cross purposes: one removed LWD to maintain flood conveyance (public safety) and the other returned LWD to maintain aquatic habitat for native fish. The programmes were paid for by separate funding sources and were for all purposes independent of one another.

In 2007, the National Marine Fisheries Service declared the instream wood management programme a violation of Endangered Species Act because the removal or cutting up of LWD could be considered harm, one of the definitions of ‘take’ under the act, to threatened and endangered species (Santa Cruz County, 2009a). In response, Santa Cruz County revised the programme in 2009 so that only LWD posing a clear threat to public safety, infrastructure or aquatic habitat could be removed and only after consultation with state and federal agencies. Nonetheless, the main factor leading to conflicts with in-channel LWD is undersized culverts and bridge openings, which was not addressed in the revised guidelines. With the 2003 Soquel Drive Bridge replacement designed to pass LWD, the most restrictive points in the channel network are now the many culverts too narrow to pass water-borne LWD.

A logical extension of the revised wood management programme would be to enlarge infrastructure to permit LWD to pass downstream and reduce the probability of water-borne LWD becoming a ‘threat to public safety or infrastructure.’ This would obviate the need to remove LWD from channels and would reduce LWD-related flooding damages. It would also restore LWD flux (input, storage and transport) through the system, supporting the creation and maintenance of aquatic habitat. In this study, we examined the sizes of bridge opening and culverts throughout the Soquel Creek basin and compared them with the size of LWD that could be transported to the infrastructure from upstream.

METHODS

Along two 2-km reaches in Amaya Creek and East Branch Soquel Creek (Figure 1), we compared the piece length to the width of infrastructure (bridges and culverts) intersecting the channel network. We then estimated the costs to enlarge (if necessary) each structure to allow downstream passage of LWD and compared these to the estimated costs of removing LWD from the channel, damages from LWD-related flooding and habitat loss.

Feasibility of infrastructure to pass large woody debris

To determine the feasibility of infrastructure to pass LWD, we compared the length of LWD to the dimensions of infrastructure intersecting the channel network. We defined LWD as pieces of wood >1 m length and >10 cm diameter (Harmon *et al.*, 1986) and counted and measured

DOI: 10.1002/rra

LWD within 1 m of the bankfull channel. For each piece, we measured the total length from just above the root swell (if rootwad attached) to the opposite end and the diameter at each end. When we encountered entire trees that tapered into a diameter <10 cm, we excluded the length of the tree <10 cm diameter.

We obtained the dimensions of infrastructure throughout the basin through a combination of field surveys and literature review. We identified potential structures on topographic and street maps and then visited them in the field to record infrastructure type and dimensions. We also consulted a basin-wide survey of bridges and culverts as potential passage barriers (Ross Taylor and Associates, 2004) as a check that we had not missed any structures and California Department of Transportation (CalTrans) bridge inspection reports (CalTrans, 2009a) to verify dimensions. We calculated the percentage of logs longer than structure width and assumed that structures with higher percentages were more prone to plugging during floods.

Estimated costs of infrastructure replacement

We estimated the cost of bridge replacement as a function of structure dimensions as a simple way to compare relative cost differences between existing and larger-sized infrastructure. We used a simple formula from Rhodes and Trent (1993)

$$\textit{Bridge replacement cost} = C_b * W_b * L_b \qquad (1)$$

where C_b = bridge rebuilding constant in $\$\,m^{-2}$, W_b = bridge width (m) and L_b = bridge length (m). Rhodes and Trent (1993) used a rebuilding constant of $\$645\,m^{-2}$ in 1993, which included materials, labour and permitting costs and was based upon a review of Federal Highway Administration data. We used separate rebuilding constants for full-spanning and partial-spanning bridges based upon CalTrans 2008 Construction Statistics, which gives high-end and low-end material cost estimates for 11 common bridge types used on California highways (CalTrans, 2009b). Factors triggering high-end costs include long spans, high structure height and environmental constraints; factors for low-end costs include short spans, low structure height and no environmental constraints. Accordingly, we used rebuilding constants of $\$3425\,m^{-2}$ for full-spanning and $\$1950\,m^{-2}$ for partial-spanning bridges, the averages of the high-end and low-end cost estimates.

For culverts, we used the formula

$$\textit{Culvert replacement cost} = \left(C_{c(w)} * L_c\right) + \left(C_r * L_c * W_c\right) \qquad (2)$$

where $C_{c(w)}$ = culvert cost (\$) per length (m) (scaled by opening width [m]), L_c = culvert length (m), C_r = roadway material cost ($\$\,m^{-3}$) and W_c = culvert width (m).

We determined the cost per length of culvert, scaled by opening width, using the United States Forest Service Cost Estimating Guide for Road Construction (USFS, 2009). We also determined the cost of overlying roadway needed to cover a culvert, ($C_r * L_c * W_c$), assuming that the volume of necessary material was equal to a 1-m depth multiplied by culvert width and length (i.e. culvert buried 1 m deep). We estimated the cost of overlying roadway ($\$184\,m^{-3}$ Portland concrete cement [pavement]) using the CalTrans price index for selected highway construction items for the fourth quarter ending December 2009 (CalTrans, 2010).

We estimated the cost to replace each culvert with a similarly sized structure and a larger structure that would allow a greater proportion of the LWD load to pass. In cost, our estimates of larger structures, we considered that different size channels have varying capacity to transport wood (i.e. narrower channels would transport shorter pieces than wider channels). Field and laboratory studies indicate that most fluvially transported pieces are shorter than bankfull width, as larger pieces may become obstructed by channel features or by contact with adjacent banks (Bilby, 1984; Lienkaemper and Swanson, 1987; Braudrick and Grant, 1997). Accordingly, a structure should be at least as wide as bankfull width. Still, Flanagan *et al.* (1998) found that most LWD plugging culverts in several national forests in the western United States was only slightly longer than culvert diameter. As a conservative estimate of minimum structure width for the LWD-passing approach, one that would pass a large proportion of in-channel LWD and be consistent with channel dimension, we used either 1.5 times the bankfull channel width or the 75th percentile log length, whichever was shorter. We believed that these minimum size criteria would pass a large proportion of the LWD load and assist in choosing a practical structure size (e.g. to avoid suggesting a 15-m structure on 3-m bankfull width channel). For this exercise, we simply used the size distribution of LWD reflecting natural recruitment (reflected by the Soquel Demonstration State Forest channels), because in this basin, the bridges and culverts were located in downstream channels that could carry the full range of sizes. However, for culverts on small channels, it would make sense to use an estimate of LWD size that reflected the size that could be transported by the channel, which would normally be limited to approximately the channel width.

Estimated costs of large woody debris removal

The total cost of LWD removal included the costs of programmatic LWD removal, LWD-related flooding and the loss of habitat associated with LWD removal. The costs of programmatic activities were obtained from publicly available yearly budgets published by Santa Cruz County, and flooding costs were estimated from flood control reports

DOI: 10.1002/rra

issued by the United States Army Corps of Engineers (USACE) in 1966 and 1983. We adjusted these estimates to 2009 by scaling the change in the Consumer Price Index (CPI) from 1966 and 1983 to 2009 (Federal Reserve Bank of Minneapolis, 2009). We estimated lost habitat using data from Leicester (2005), who surveyed mainstem Soquel Creek (Figure 1) and several nearby creeks not subject to instream wood management (unmanaged). We compared LWD loading (pieces m^{-1}) between mainstem Soquel Creek and the unmanaged creeks and assumed differences were due to instream wood management. We then estimated the cost of restoring LWD loading in mainstem Soquel Creek to equal the loading in unmanaged streams. We assumed a scenario whereby loading was restored with instream structures and single logs (habitat restoration). To quantify the cost of lost habitat, we estimated the cost of 'restoring' habitat, based upon Hildner and Thomson (2007), who analysed restoration projects in the California Habitat Restoration Project Database and calculated average cost for different types of restoration activities.

RESULTS

Feasibility of structures to pass large woody debris

Along Amaya Creek and EBSC, we counted 617 pieces of LWD with a median length of 4.6 m and 75th percentile length of 9.0 m. Data from the two reaches were lumped because the entire population represents pieces that may interact with infrastructure, not LWD loads from individual reaches.

We identified and measured nine culverts and three bridges intersecting the channel network (Figure 1, Table 2). Culvert opening widths ranged from 1.8 to 3.7 m wide and were narrower than 59–87% of LWD pieces. Bridge opening widths ranged from 7 to 44 m wide and were narrower than 1–32% of LWD pieces. The bridges with the widest spans, the Porter Street and Soquel Drive bridges, were built recently in 1994 and 2003 and were wider than 99% of all pieces. The Stockton Avenue Bridge (built in 1926) had three openings created by support piers. Each opening was separately compared to LWD piece length with the centre opening narrower than 3% of pieces and the side openings narrower than 32%. We compared the median length of LWD to the bankfull channel width of each stream with a culvert and used the greater value as a potential opening size for infrastructure. All culverts were narrower than bankfull width and 75th percentile piece size (9.0 m; Table I).

Estimated costs of structure replacement

We estimated structure replacement costs under three management scenarios: (i) historical (current culvert sizes and partial-spanning bridges); (ii) current (current culvert sizes and full-spanning bridges); and (iii) LWD-passing (culvert opening = 75th percentile LWD length 9.0 m) or 1.5 times the bankfull width [whichever was smaller] full-spanning bridges) (Table II). Estimated current management costs ($7 080 000) increased 41% over historical ($4 180 000), whereas LWD-passing costs ($7 510 000) were 44% greater than historical and 3% greater than current.

Estimated costs of large woody debris removal

Programmatic flood control activities. The estimated cost of programmatic flood control activities within the Soquel Creek basin was $16 400 year^{-1}. We used estimates from 2005 to 2009 for Santa Cruz County's Flood Protection Zone 4 logjam removal programme, the programme under which logs are removed for flood control purposes (Santa Cruz County, 2005, 2006, 2007, 2008, 2009b). The programme covered all of Santa Cruz County and the budget ranged from $64 000 to $70 000. We did not apply this entire cost to Soquel Creek but assumed that the budget was split evenly among four major river basins within Santa Cruz County (Aptos, San Lorenzo, Soquel and Pajaro). We did not prorate the budget according to basin area or stream length in order to give a conservative estimate for LWD removal activities and to recognize that LWD dynamics within individual basins, regardless of area, is the major driver behind LWD management. This estimate does not include emergency LWD removal during floods, only programmatic activities that are anticipated in annual budgets. Episodic removal during floods likely increases the estimate. After revising instream LWD management practices in 2009, Santa Cruz County allocated $30 000 for the Zone 4 logjam removal programme for fiscal year 2009–2010 (Santa Cruz County, 2009b). Dividing total amount among the four major basins within Santa Cruz County leaves an estimated annual cost of $7500 year^{-1}.

Costs of large woody debris-related flooding. The estimated costs of LWD-related flooding were $217 000 year^{-1} or $11 700 000/54 years. This estimate is based upon LWD-related flood damage from 1955 and 1982, the two largest floods of record in the Soquel Creek basin and floods that were accompanied by a large logjam at the Soquel Drive Bridge. Because the flooding and related damage were episodic, we prorated the costs over the time period from the first flood until the present (54 years). In examining the 1955 flood and exploring future flood control options, the Army Corps estimated flood-related damages of $6 800 000 [Scaled from $1 000 000 in 1965 dollars to 2009 dollars; 2009 CPI (213.2)] / [1965 CPI (31.5) = 6.8] (USACE, 1966; Federal Reserve Bank of Minneapolis, 2009). The Army Corps also issued a report after the 1982 flood estimating damages to the town of Soquel of $4 900 000 [Scaled from $2 200 000 in 1982 dollars to 2009 dollars; 2009 CPI

DOI: 10.1002/rra

Table I. The width of culvert and bridge openings, proportion of large woody debris (LWD) longer than each opening width and the estimated cost to replace infrastructure

Location	Width of existing opening (m)	Bankfull width (m)	Length of existing structure (m)	Per cent LWD blocked[a]	Historical approach [b]	Current approach[c]	LWD-passing approach[d]
Bates Cr 1	2.4	3.3	17	77	19 200	19 200	38 100
Bates Cr 2	2.4	3.3	12	77	13 500	13 500	26 900
Moore Cr 1	2.6	4.4	52	76	63 100	63 100	153 000
Moore Cr 2	1.8	4.4	12	87	10 300	10 300	35 300
Moore Cr 3	1.8	4.4	12	87	10 300	10 300	35 300
Hester Cr	3.7	4.3	27	59	45 400	45 400	77 100
W B Soquel Cr	3.7	7.1	31	59	52 100	52 100	124 000
Laurel Cr 1	3.1	7.5	25	68	35 500	35 500	99 600
Laurel Cr 2	2.4	3.6	69	77	77 800	77 800	167 000
Porter Street	41	15.0	20	1	1 600 000	2 810 000	2 810 000
Soquel Drive[e]	44	15.0	18	1	1 550 000	2 710 000	2 710 000
Stockton Ave[f]	39	15.0	9	1	703 000	1 230 000	1 230 000
Total					$4 180 000	$7 080 000	$7 510 000

[a]Proportion of LWD longer than opening width under current conditions.
[b]Historical management: current culvert sizes and partial-spanning bridges.
[c]Current management: current culvert sizes and full-spanning bridges.
[d]Managed to pass 75th percentile LWD length (9.0 m) or 1.5 times bankfull width, whichever is smaller, and full-spanning bridges.
[e]Historical bridge dimension included two spans 26 and 10 m, blocking 2 and 20% of LWD.
[f]Current bridge dimension includes three spans 24, 7 and 7 m wide, blocking 3, 32 and 32% of LWD.

(213.2)] / [1965 CPI (96.5) = $4 900 000] (USACE, 1983; Federal Reserve Bank of Minneapolis, 2009). We assumed that most damages were due to the logjam at the Soquel Drive Bridge.

Costs of lost habitat. Large woody debris loading in mainstem Soquel Creek (0.007 pieces m^{-1}) was an order of magnitude lower (0.054 to 0.106; 0.087 average) than all other streams surveyed by Leicester (2005) (Figure 3). These natural LWD loading rates applied to mainstem Soquel Creek would yield a potential LWD abundance of 888 to 1738 pieces, but actual LWD abundance was only 113 pieces for the entire 16.4-km reach. From this, we calculated a 'LWD deficit', the difference between actual abundance and the abundance expected under unmanaged conditions, of 775 to 1625 (1316 average) pieces. Based upon Leicester (2005) and Lassettre *et al.* (2008), we assumed that 30% of the pieces would be found in jams of at least three pieces, and the remainder would occur as single logs. The estimated cost of each jam was $3400, based upon the median cost of wood structures calculated by Hildner and Thomson (2007) and the estimated cost of each single log was one-third the cost of a structure. The total cost of lost habitat was estimated to be $1 492 000, spread over the time period from 1971 (programme inception), the annual costs were $39 000 $year^{-1}$.

Table II. Comparison of historical, current and proposed wood-passing approach

Action	Historical approach[a]	Current approach[a]	Wood-passing approach[a]
Infrastructure replacement	83 500	142 000	150 000
Programmatic flood control	16 000	8000	8000
LWD-related flooding	217 000	159 000	150 000
LWD-related habitat loss	39 000	29 000	10 000
Annual cost (years 1–50)	356 000	338 000	319 000
50-year cost (years 1–50)	17 800 000	16 900 000	15 900 000
Annual cost (years 51–100)	356 000	338 000	206 000
50-year cost (years 51–100)	17 800 000	16 900 000	10 300 000
100-year cost	$35 600 000	$33 800 000	$26 200 000

LWD, large woody debris.
[a]Rounded to the nearest $1000.

DOI: 10.1002/rra

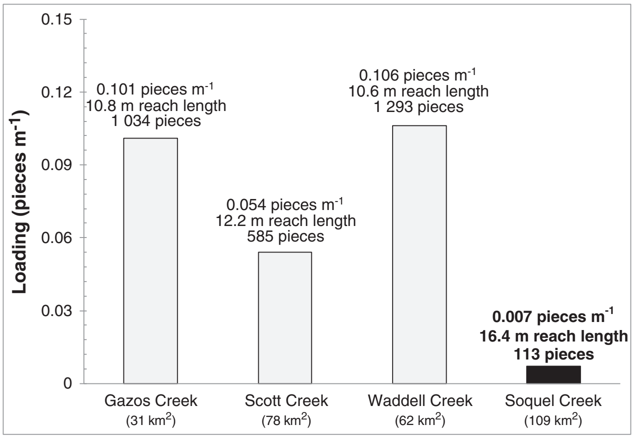

Figure 3. Large woody debris loading and abundance in Soquel Creek and unmanaged streams (basin area in parentheses below each bar; data from Leicester, 2005).

Limitations

We did not attempt to account for potential costs associated with LWD on recreational navigation or on diverting flow into banks. LWD can pose hazards to recreational boaters, and although boaters expose themselves to significant risks, it is easy to imagine (in an American context) public agencies being sued for leaving LWD in channels and causing boater impingement. Riparian property owners often demand public agencies to remove jams diverting flow towards their banks (or remove accumulated LWD themselves). We did not attempt to consider these potential costs.

Large woody debris produces ecological benefits beyond fish, by providing habitat for birds, mammals and other species. We did not attempt to capture the value of these benefits.

DISCUSSION

Comparison of instream large woody debris management approaches

Using the data and estimates previously mentioned, we compared three approaches to instream wood management on an annual cost basis and over a 50-year period: historical (used before wood management programme revision in 2009); current (LWD no longer removed, infrastructure is left in place); and a LWD-passing, where LWD is left in place and infrastructure is modified to allow passage.

Historical management relied upon removing LWD to maintain flood conveyance and was the most expensive of all approaches, costing \$356 000 year^{-1} or \$17 800 000/50 years (Table II). The largest costs were associated with LWD-related damage from large floods (\$217 000 year^{-1}), such as it occurred in 1955 and 1982. The next largest cost was infrastructure replacement (\$83 500 year^{-1} or \$2 444 000/50 years) that assumes the replacement of all culverts and bridges with similar sized infrastructure over a 50-year period (Table I). Programmatic flood control and LWD-related habitat loss are the highest under this approach compared to current and LWD-passing approach. The historical approach still resulted in two, large damaging floods and a severe loss of habitat despite being the most aggressive LWD management programme.

The current approach follows the revised 2009 instream wood management guidelines intended to increase LWD loads for fish habitat. The estimated annual cost was \$338 000 year^{-1}, lower than the historical approach, with greatest costs still associated with LWD-related flooding and infrastructure replacement (Table II). The episodic nature of large storms along the central California coast and the setting of Soquel Creek will still provide the environment for large floods, but we assumed that annual flood damage would be lower than under historical management. In the absence of a predictive tool to estimate LWD-related flooding under different management approaches, we reduced this cost by the difference in annual infrastructure replacement between current and historical management (\$58 000) assuming that infrastructural upgrades will reduce LWD-related flooding in-kind. Infrastructure replacement costs are greater than the historical approach, all culverts are replaced every 50 years with similarly sized structures, but bridges are replaced with full-spanning structures. We anticipated a reduction in LWD-related habitat loss because LWD is more judiciously removed but because restrictive culverts are not replaced, reductions in LWD-related habitat loss are limited. We scaled the anticipated LWD deficit in Soquel Creek (1316 pieces, see Costs of lost habitat) by the average proportion of LWD longer than culvert opening width (0.74, Table I) to estimate a LWD deficit under the current approach (976 pieces) and then estimated the cost of lost habitat. Programmatic flood control costs reflect 2009–2010 Santa Cruz County budget estimates (Santa Cruz County, 2009b).

We estimated \$319 000 year^{-1} for the LWD-passing approach, lower than the estimated costs for the historical and current approaches (Table II). The highest anticipated costs were replacement of current structures with larger structures and wood-related flooding, similar to the historical and current approaches. The increases in infrastructure costs would be offset by reductions in LWD-related habitat loss and flooding. We scaled the anticipated LWD deficit (1316 pieces, see Costs of lost habitat) by the predicted proportion of LWD longer than culvert opening width (0.25) to estimate a LWD deficit under the LWD-passing approach (329 pieces), then estimated the cost of lost habitat. As with the current approach, programmatic flood control costs reflect 2009–2010 Santa Cruz County budget estimates (Santa Cruz County, 2009b).

DOI: 10.1002/rra

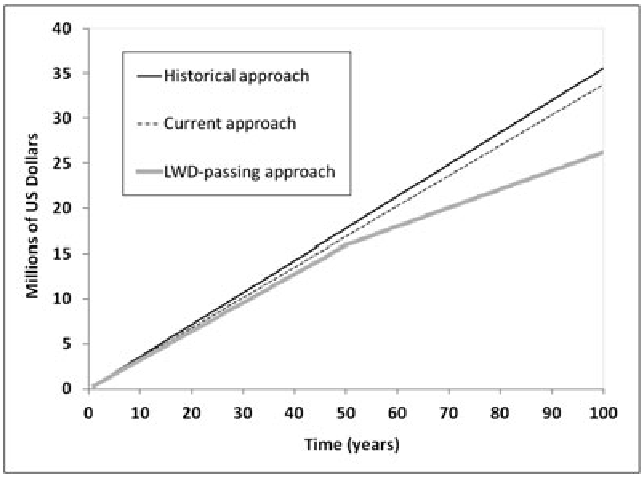

Figure 4. Costs associated with historical, current and large woody debris (LWD)-passing approaches to LWD management in Soquel Creek.

Over longer time periods, the savings and potential benefits of the LWD-passing approach increases. Table II presents costs over two time periods (years 1–50 and years 51–100) and Figure 4 shows the total cost over 100 years. Under historical and current approaches, LWD management costs are constant because LWD is still managed and infrastructure is still replaced. Under the LWD-passing approach, the fixed costs associated with structure replacement are reduced, resulting in lower long-term costs. We estimated reductions in infrastructure replacement costs of 75% for the LWD-passing approach. The wood-passing approach estimates are still conservative, still anticipating LWD-related flooding and LWD-related habitat loss, and also not incorporating added value associated with expected gains in aquatic and riparian habitat or biota. If flooding costs are further reduced because of infrastructure replacement and habitat and biota are improved, then the wood-passing approach is economically and ecologically cost effective. This example illustrates that planning based on recognition of natural processes will likely yield economic, ecological and, in this case, public safety benefits.

The idea of LWD-passing approach in the Soquel Creek Basin is not a new one. After the devastating December 1955 floods, an editorial in the Santa Cruz Sentinel stated that 'the flood also emphasized the need as dramatically shown in Soquel, for wide spans to allow sufficient clearance for debris in times of floods…New bridges will be costly but they are one of the city's greatest needs if we are to provide streets free of congestion for the years ahead (Santa Cruz Sentinel-News, 1955)'. The editorial writer in 1955 argued for large bridge openings to pass LWD strictly for public safety. Today we have another motivation: the demonstrated habitat value of LWD in the channel and the critical need to improve habitat for listed fish species. The revised LWD management currently implemented (i.e. leave LWD in the channel) recognizes the ecological value of LWD but does not address undersized infrastructure. Leaving LWD in the channel with undersized infrastructure will inevitably lead to future flood conveyance conflicts. Viewed over a sufficiently long time scale, it makes environmental and economic sense to modify infrastructure to reduce such conflicts. Our results show that investments in enlarging bridges and culverts to pass LWD are more than compensated by lower annual maintenance costs over a 50-year period in Soquel Creek.

Soquel Creek is probably typical of many streams in its history of LWD management and in its potential to pass LWD if bridge and culvert openings were enlarged. Given the urgent need to maintain and restore habitat for listed salmonid species in many rivers, the approach proposed here may have broad applicability.

ACKNOWLEDGEMENTS

We thank the California Department of Forestry and Fire Protection for funding support and the opportunity to conduct research within the Soquel Demonstration State Forest (SDSF); thanks to SDSF Forest Manager Thom Sutfin. We also thank two anonymous reviewers for comments and suggestions that improved this paper.

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