Effects of Riprap Bank Reinforcement on Stream Salmonids in the Western United States

Article *in* Fisheries · July 2001

DOI: 10.1577/1548-8446(2001)026<0006:EORBRO>2.0.CO;2

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ABSTRACT

Angular rock riprap is used to reduce riverbank erosion in developed riparian corridors. We reviewed peer reviewed as well as non-refereed literature to determine the effects of riprap on salmonid habitat and populations and to identify areas for future (applied) research. Although commonly used to armor banks, riprap affects salmonid populations and stream function. Riprap may provide habitat for juvenile salmonids and bolster densities on reaches of streams that have been severely degraded. However, riprap does not provide the intricate habitat requirements for multiple age classes or species provided by natural vegetated banks. Streambanks with riprap have fewer undercut banks, less low-overhead cover and are less likely than natural stream banks to contribute large woody debris to the stream. Lateral streambank erosion is a natural process that occurs in many stream types. However, most valley-bottom stream types, which have the greatest tendency to laterally migrate, lie within developed corridors. Although permitting of individual projects may attenuate localized negative effects to streambanks, it may not effectively curtail cumulative effects to a watershed. Our review further demonstrated that the practice of riprapping banks goes against current practices and philosophies of stream renaturalization and impedes future restoration work. Future research should determine the true effects of riprap banks on salmonid densities, the use of soft techniques using for stabilizing banks on rivers, and the cumulative effects of riprap projects on watersheds and fluvial processes. We foresee a continued struggle for resource managers trying to maintain natural fluvial processes while protecting public infrastructure and private property from those same processes.

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Introduction

Many land management practices have transformed rivers and, consequently, few streams and watersheds currently exist in their natural states (Heede 1986). Fish habitat loss and degradation is responsible for the decline of many native salmonids in the western United States (Minckley et al. 1991; Behnke 1992; Rieman and McIntyre 1993). Fish habitat loss is usually a result of anthropogenic disturbance and can vary from loss at the watershed scale to the river reach level. Resource managers must work in these altered conditions to meet often-divergent goals of maintaining natural fluvial processes, yet protecting public infrastructure and private property from those processes.

For centuries, humans have struggled with near-river development and natural fluvial processes that form floodplains. Civil engineers seldom have used natural channel designs in solutions to development along waterways (Heede 1986; Mount 1995). Land use practices that have eliminated or reduced riparian vegetation can accelerate the rates of natural lateral erosion (Platts and Rinne 1985). In developed riparian corridors, private property and public infrastructure often encroach on rivers and streams, and these structures (i.e., bridges, roads, private land) sometimes must be protected (Heede 1986). Applying large angular rock (riprap) to armor stream banks is a common practice to reduce erosion and flooding on rivers and streams throughout the United States (Figure 1).

Riprap is relatively inexpensive and effective at controlling erosion compared to other bank stabilization techniques (Beschta et al. 1995). For these reasons, riprap bank reinforcement is common in Montana (Montana Fish, Wildlife and Parks, unpublished data) and elsewhere. For example, in Missoula County in western Montana, 215 bank stabilization projects were evaluated on five major waterways (Brandt and Ringelberg 1999). Of these, 194 (90%) incorporated riprap as the primary material influencing 41.5 km (21%) of the 194 km surveyed (Brandt and Ringelberg 1999).

The extent to which riprap affects stream function and salmonid populations is not well studied. Increasingly, managers are critically reviewing how floodplains might be restricted, fluvial processes altered, and salmonid habitat is affected by riprap. Here, we describe how riprap bank reinforcement contributes to salmonid habitat loss for coldwater fisheries in the western United States and the subsequent effects to fish populations. The objectives of this paper are to summarize existing literature on the effects of riprap on salmonid habitat and salmonid populations and identify areas for future (applied) research.

Streambanks and bank stabilization

Woody vegetation and complex root systems are essential for sustaining bank integrity. Abundant woody vegetation and root aggregations slow the erosion cycle and increase bank roughness thereby dissipating stream energy during high flows. Whereas sod mats maintain banks in low gradient streams, higher gradient streams are dependent on woody vegetation and root systems for holding banks together (Hickin 1984; Figure 2). The average critical bank sheer stress for riverbanks covered by vegetation with well-developed root networks is about three times that of rivers with weakly vegetated, grass covered banks (Millar and Quick 1998).

Loss of riparian vegetation can lead to simplified aquatic habitat and may reduce the potential for large woody debris (LWD) recruitment into the stream (Ralph et al. 1994; Young et al. 1994; Fausch et al. 1995). Many streams lack sufficient large organic material for biotic and abiotic functions (Beschta and Platts 1986). The importance of large woody debris for salmonid habitat is well documented (Meehan 1991). By riprapping banks, LWD recruitment is eliminated because lateral migration is stopped and less LWD and plants become established than on natural banks (Dykaar and Wigington 2000).

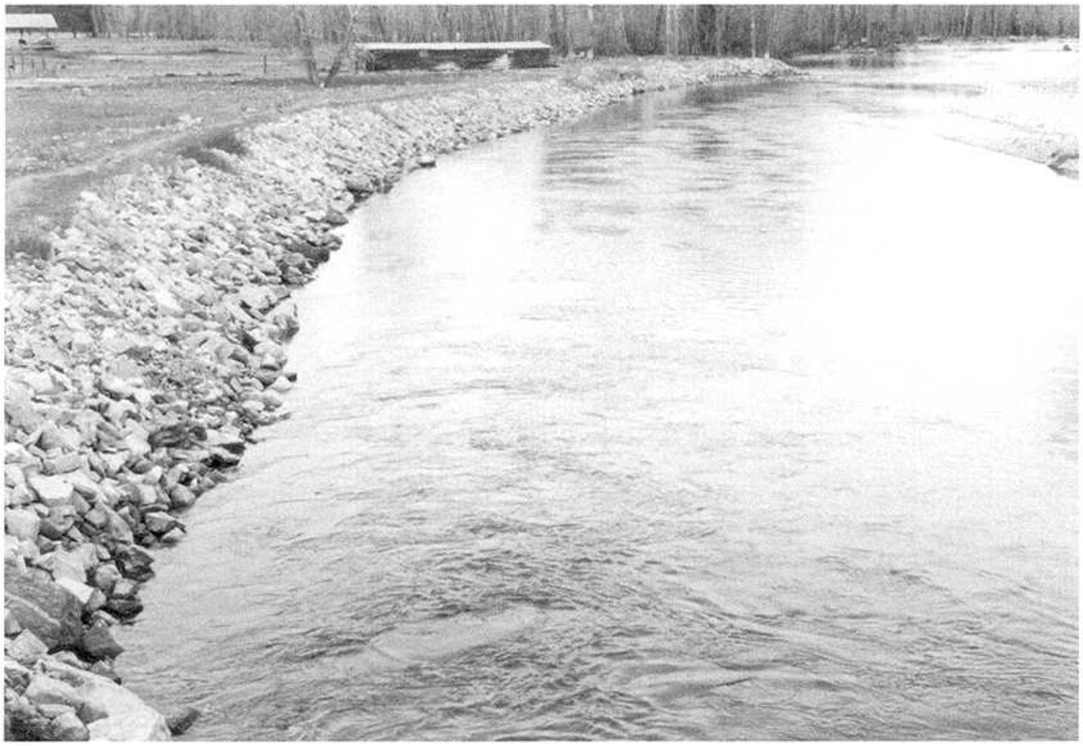

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Figure 1. This conventional riprap project is on the Bitterroot River, Montana.

Riparian vegetation and undercut banks contribute to salmonid habitat complexity. Riparian vegetation protects banks from erosive forces. Complex root systems hold bank materials in place and riparian plants, e.g., willows (*Salix* spp.) and black cottonwoods (*Populus trichocarpa*), protect banks from erosive overland flood flows. Riparian vegetation also shades water, thereby ensuring cooler summer water temperatures for stream-dwelling salmonids. Aquatic and terrestrial insects using streamside vegetation are food for stream fishes. Undercut banks provide cover from predators and refuge from high flows for resting and feeding salmonids.

The placement of riprap without revegetating the project site reduces the amount of riparian vegetation (Peters et al. 1998), which may remain barren for extended time periods (Brandt and Ringelberg 1999; Dykaar and Wigington 2000) compared to natural banks. Evaluated riprap projects on Missoula County, Montana waterways rarely supported riparian vegetation aside from exotic plants (Brandt and Ringelberg 1999). Riprapped banks have reduced black cottonwood regeneration to a small fraction of historic levels on the Willamette River (Dykaar and Wigington 2000).

Alluvial channel patterns adjust by lateral channel migration and longitudinal profile changes through aggradation and degradation (Leopold et al. 1964; Knighton and Nanson 1993; Alabyan and Chalov 1998). Natural formations such as bedrock and unnatural treatments such as riprap force streams to maintain alignment (i.e., no migration or meandering) and limit lateral channel adjustments, including gravel entrainment. Extensive riprapping, which leads to straightening of the stream reach, will also lead to increasing gradient (Simons and Richardson 1966; Heede 1986). In fine-grained stream reaches, when streams are prevented from lateral adjustments they can start to incise (adjust downward, rather than laterally) which may cause a series of morphological changes: floodplain abandonment, bank steepening and erosion, lowering of the water table, changes in stream bank vegetation, and change in stream substrate. Such morphological adjustments often migrate upstream and are apparent far from the site where the bank alteration occurred (Beschta and Platts 1986; Heede 1986). Riprapping streambanks can lead to increased erosion on the opposite bank downstream of riprap projects (M. Miles, Mike Miles and Associates, Ltd., Victoria B. C., pers. comm.). A more thorough review of these fluvial processes related to riprapping is beyond the scope of this paper.

Riprap characteristics contrast with the features of complex LWD structures to the detriment of aquatic organisms. Interstitial spaces are maximized in dense LWD such as rootwads; similar microhabitats are less available in riprap projects (Peters et al. 1998). Salmonid densities were generally lower at stabilized sites except when LWD was incorporated in the project design (Peters et al. 1998). Sub-yearling trout and salmon densities were lower at stabilized banks than at nearby control sites. Spatially continuous riprap projects maintained lower sub-yearling and juvenile salmonid densities in the Willamette River because of the adverse microhabitat conditions created by large angular rock (Li et al. 1984). Conversely, yearling and older trout densities were unaffected or increased at bank treatment sites compared to control sites (Peters et al. 1998). Sub-yearling chinook (O. *tshawytscha*), coho (O. *kisutch*), and rainbow trout (O. *mykiss*) responded similarly while yearling and older rainbow trout densities did not differ significantly between stabilized and control sites (Beamer and Henderson 1998).

Riprap bank stabilization was identified as a primary cause for the decline of salmon in the Sacramento River, California.

Effects of riprap on salmonid habitat and populations

As previously summarized in the discussion of LWD, riprap, by design, eliminates lateral bank erosion at treatment locations, which prevents the development of undercut banks and overhead cover. Undercut banks provide important summer habitat for stream salmonids (Brusven et al. 1986; Beamer and Henderson 1998). Overhead bank cover provided primarily by riparian vegetation was related to greater brown trout (*Salmo trutta*) abundance in small Wyoming streams (Wesche et al. 1987). Overhead bank cover declined 88% and 50% in two study reaches of Millville Creek, Wisconsin, two years after the installation of riprap (Avery 1995).

By changing stream reach sediment transport capacity and introducing large angular rock, the bed load size and particle distribution can be moved outside the natural range of sediment sizes for a particular stream reach (Beschta and Platts 1986). Simplification of available sediments may have consequences for salmonid persistence. Salmonids rely on various particle sizes for complex needs: food, cover, and spawning. Salmonids have adapted to the availability of the natural distribution of particle sizes for aspects of their lives (Platts 1979; Beschta and Platts 1986). Because of these diverse needs, no single particle size will create ideal habitat for growth and survival (Beschta and Platts 1986). Riprap homogenizes the bank material and habitat features (Dykaar and Wigington 2000).

Channel substrate is a significant habitat variable describing salmonid spawning site selection (Cummins 1974). Large substrates that exceed a fish's ability to mobilize them are avoided during redd building (Kondolf and Wolman 1993). However, finer sediments are also problematic for spawning success because of the greater likelihood of siltation and egg smothering (Cooper 1965; Chapman 1988). These two requirements result in a generally narrow range of sediment sizes acceptable for high spawning success.

Golden trout (O. *mykiss aguabonita*) specifically require lateral erosion to create spawning habitat (Knapp et al. 1998). The loss of woody vegetation from riparian zones can eliminate the potential LWD input that is essential for trapping and retaining gravels instream (House and Boehne 1985; Murphy and Koski 1989). The absence of instream LWD can lead to the loss of spawning habitat for fluvial westslope cutthroat trout (*Oncorhynchus clarki lewisi*), which spawn in freshly deposited bedload material (Schmetterling 2000). Riprap bank stabilization was identified as a primary cause for the decline of salmon in the Sacramento River, California (Buer et al. 1984). On one 100-km reach of the Sacramento River, 25 km of riverbank was riprapped which eliminated the re-entrainment of gravels necessary for creating salmon spawning habitat (Shields 1991). Prior to riprap bank stabilization in the Sacramento River drainage, the most important source for spawning gravels was from bank erosion (Buer et al. 1984). Riprap bank stabilization effectively reduced the input of gravels into this system and eliminated significant amounts of salmon spawning habitat.

Converse to the narrow range of sediment size acceptable for spawning, salmonids rely on a variety of particle sizes for feeding and cover requirements (Platts 1979; Beschta and Platts 1986). Cobbles and boulders provide flow breaks important for shelter and feeding stations. Larger substrates may also be important during the winter months when salmonids minimize energy expenditures by diurnally hiding in the substrate (Jakober et al. 1997).

Alteration of fish habitat may favor invasive fishes (Moyle and Light 1996). For example, exotic fishes were abundant in riprap substrate and were rarely seen in other sampling locations (Jude and DeBoe 1996) in the St. Clair River in Michigan. Trends associated with native fish replacement by exotic fishes may also be prevalent in western salmonid-dominated streams already converted to exotic game-fish fisheries (Behnke 1992). For example, densities of introduced brook trout (*Salvelinus fontinalis*) increased after reaches of Beaver Creek, Wyoming were riprapped (Binns and Remmick 1994). Jude and DeBoe (1996) caution fishery managers that riprap may favor undesirable species.

Riprap provided significantly less cover than vegetative stabilization in a small Montana stream. Also, densities of juvenile rainbow trout and brown trout (*Salmo trutta*) associated with riprapped banks did not recover from drought and irrigation dewatering as fully when compared to densities associated with vegetative treatments and natural banks. However, there were no significant differences in densities of trout between all sites due to severe dewatering impacts (McClure 1991). Streambanks with riprap had lower densities of rainbow trout than streambanks with natural cover in the Wood River, Idaho (Thurow 1988). Densities of coho salmon, juvenile steelhead, and cutthroat trout (O. *clarki*) declined following riprap installation in five study streams in western Washington (Knudsen and Dilley 1987). The impact to salmonids was greater on small streams than large streams and greater to juvenile salmonids than adults (Knudsen and Dilley 1987).

Confounding factors

Two well documented cases of salmonid population declines in response to bank stabilization occurred in Montana, which illustrates problems with confounding variables. The impact of highway construction alone led to major trout reductions in streams that were channelized (Whitney and Bailey 1959; Elser 1968). Elser (1968) quantified the relationship of salmonid populations to channel alterations in Little Prickly Pear Creek, Montana. The channel alterations in this case resulted from highway construction where reaches were channelized and banks stabilized with riprap. Salmonids and native non-salmonids were significantly less abundant or absent (respectively) from the altered compared to unaltered reaches. However, in each of these cases, riprap was not the only treatment. Similarly, in small streams (discharge < 0.3 m^3/s) in western Washington, losses of salmonid production resulted from channelization (Chapman and Knudsen 1980). While riprap bank reinforcement was used to maintain channel alignment, these streams were channelized (and in some cases diked) and therefore the conflicting variables cannot be separated.

In some instances, salmonid abundance may increase after stream banks are riprapped. Brown trout densities increased significantly after installation of riprap in Millville Creek, Wisconsin (Avery 1995). However, Millville Creek had historical streambank damage caused by livestock use (E. Avery, Wisconsin DNR, pers. comm.). Furthermore, no control sites that were unimpacted by grazing were available for study. Similarly, Bonneville cutthroat trout (O. *clarki utah*) and brook trout densities increased in Huff and Beaver Creeks, Wyoming, respectively, several years after drainage-wide habitat management, including long reaches of riprap were added (Binns 1994; Binns and Remmick 1994). In Huff Creek, historical grazing had damaged salmonid habitat and riprap provided cover for Bonneville cutthroat trout. However, proper grazing management also benefited populations of Bonneville cutthroat trout in Huff Creek (R. Remmick, Wyoming Game and Fish, pers. comm.). Juvenile rainbow trout showed selection for riprapped banks, which suggests that they are not affected by modified banks if the size of the bank material is large enough. Large size riprap supported higher numbers of juvenile salmonids than smaller

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Figure 2. In this undisturbed streambank in the foreground and a riprapped streambank in the background, note the absence of low overhead cover, undercut bank and potential for woody debris recruitment of the riprapped bank compared to the undisturbed bank.

size riprap and cobble-boulder material (Li et al. 1984; Lister et al. 1995; Peters et al. 1998).

Despite the increases in densities of salmonids in impaired streams, when different bank reinforcement techniques were compared for several streams in western Washington, fish used riprapped banks less often than natural banks (Beamer and Henderson 1998; Peters et al. 1998). Riprapped banks that included LWD or riparian vegetation lessened the effects of riprapping on salmonid abundance. However, despite the amount of vegetation added to riprapped banks, salmonid abundance was less at banks modified with riprap compared to natural banks (Peters et al. 1998).

Alternatives to riprap

Because of scale, riprapping may be less detrimental to large streams than it is to small streams (Knudsen and Dilley 1987). However, the cumulative effects of large-scale riprapping may be detrimental regardless of stream size. Riprap becomes more common as cumulative effects of urbanization increases along streams (May 1996). In most areas, allowing channel migration within the floodplain is important for the integrity of physical and biological stream components. Although permitting of individual projects may attenuate localized negative effects to streambanks, it may not effectively curtail cumulative effects to a watershed (Stein and Ambrose 1998). In one instance, a management plan was devised that allowed for bank protection in some reaches and prohibited bank protection measures in reaches with actively mobile meanders (Piegay et al. 1997). This arrangement was made possible through a contract between managers and riverside landowners by which managers purchase conservation lands while landowners receive indemnities for reduced usage rights.

Incorporating large and dense woody debris provides stable habitat for rearing sub-yearling fish that are otherwise vulnerable to predation and flow displacement.

The use of natural materials (i.e., LWD, trees, rootwads, etc.) in bank reinforcement and restoration is a growing practice. These "soft" techniques aim to slow the rate of erosion rather than completely stop lateral erosion (Hunter 1991; Goodwin et al. 1997; Peters et al. 1998). The establishment of sound vegetation on banks is the ultimate goal in many restoration projects (Heede 1986). By accounting for geomorphic channel type (e.g., Rosgen 1994) and fluvial processes (Heede 1986), it appears that salmonid habitat can be effectively restored and maintained through major flood events on small (<1.0 m^3/s) streams (Schmetterling and Pierce 1999) where sheer stresses are less (T. Sylte, United States Forest Service, Lolo National Forest; pers. comm.). However, these practices are not as well proven as riprap (see Frissell and Nawa 1992) for stabilizing banks. From a landowner's perspective there is more risk in using these techniques and it is often more expensive. It appears that incorporating natural materials (i.e., LWD) into bank stabilization projects will assuage habitat losses (Beamer and Henderson 1998; Peters et al. 1998).

There is a growing understanding of the importance of LWD for mitigating the loss of salmonid habitat when natural banks are stabilized (Peters et al. 1998). Whereas the incorporation of woody material in a project is important, the placement of the debris is equally critical. Placing woody debris to provide habitat during both summer low flows and spring high flows maximizes LWD benefits to fish assemblages (Peters et al. 1998). Incorporating large and dense woody debris provides stable habitat for rearing sub-yearling fish that are otherwise vulnerable to predation and flow displacement.

Discussion

Riprap is a commonly used technique for stabilizing eroding banks in the western United States (Peters et al. 1998; Brandt and Ringelberg 1999). The effects of this treatment on dynamic channel processes and salmonid fisheries in the region are understudied. Whereas past investigations have explored stream channelization effects, a limited number of projects have identified the consequences of riprap stabilization on biological and physical stream attributes. The cumulative effects of numerous projects on a stream are even less represented in the literature. Despite the widespread use of riprap we were surprised by how few comparative studies there are on the subject. However, studies that quantitatively investigate the effects of riprap on fish densities largely suggest a preponderance of evidence against the continued use of riprap along rivers and streams (Li et al. 1984; Peters et al 1998; Beamer and Henderson 1998).

Habitat availability and quality is not apparent or well quantified in many studies we reviewed. In a severely degraded stream, introduced large angular rock may provide interstitial spaces for young-of-year salmonids and may improve habitat quality (Avery 1995) because large substrates can allow for fish utilization of interstices (Beamer and Henderson 1998). Although in some instances densities of salmonids increased after riprapping, this does not suggest that it is a good ecological practice. Furthermore, these increases may be a reflection of observed increased salmonid densities at a relatively small scale, which may be meaningless because habitat degradation and perturbations occur at often a much larger scale. Nevertheless, riprap does not provide the intricate habitat requirements for multiple age classes or species similar to natural banks, or banks that include LWD (Peters et al. 1998).

Surprisingly, although riprapping banks is common, the effects on fish populations and even fluvial processes are often poorly identified and quantified. The intent of riprap is to stabilize stream channels and limit natural fluvial processes. The reduction of the erosion and consequent deposition cycle, naturally inherent to all alluvial channels, eliminates a channel's ability to maintain bedforms for salmonid habitat and impairs the ability for a stream to be maintained in a dynamic steady state (Beschta and Platts 1986; Heede 1986). This alteration of the aquatic ecosystem has diverse deleterious effects on aquatic communities, ranging from carbon cycling to altering salmonid population structures and fish assemblages.

Several areas received little or no attention in the literature, such as the true effects of riprap banks on salmonid densities, the use of soft techniques using for stabilizing banks on rivers, and the effects of riprap on watersheds or away from treated banks. The study of salmonid densities around riprap banks is often confounded by other perturbations such as diking and channelization. Studies should focus on the true effects of riprap that are separate from other variables. Confusing from our review was while some studies found different salmonid population responses to riprap; the cumulative effect of riprapping banks at the drainage or watershed levels is unknown. Future studies should attempt to quantify or examine the impacts upstream and downstream of riprap projects and should include case studies. Watershed level assessments to examine the cumulative impacts of riprap on stream geomorphology, riparian condition, and large woody debris recruitment are needed. Until these gaps in the literature are filled, our understanding of the effects of riprap and other options for controlling erosion will be less clear.

A growing body of literature suggests that in small streams, soft techniques for bank stabilization and fish habitat improvements are successful (e.g., Beamer and Henderson 1998; Peters et al. 1998; Schmetterling and Pierce 1999). As a result, it seems imperative to discontinue the use of riprap on small streams in favor of the use of natural materials. While there is some support to use locally appropriate natural materials and soft techniques for bank stabilization, resistance to their use exists. Institutional, political and psychological barriers to widespread adoption of bio-technical approaches by the civil engineering community are deep-seated (Shields et al. 1995).

The interdependency between stream and riparian systems must be balanced for a harmonious equilibrium to be established (Platts and Rinne 1985; Heede 1986). While stream restoration is a growing practice in the Northwest (Frissell and Nawa 1991; Beschta et al. 1995), the restorative potential of a stream is affected by riprap (Dykaar and Wigington 2000). Re-naturalizing river reaches by providing space for natural processes to re-establish channel morphologies and associated habitat may be more successful than restoring localized fish habitat (Kellerhals and Miles 1996). Along many major rivers, bank stabilization has become so extensive that removal or drastic modification of bank protection structures is necessary to restore potential for geomorphic changes (Bravard et al. 1986; Dykaar and Wigington 2000).

Preventing floodplain development through public education and governmental regulations will reduce the need for further bank stabilization. Discouraging floodplain property development is a sound goal to follow. Designing management plans that incorporate the unpredictability of rivers and streams is essential where development already exists (Piegay et al. 1997). Furthermore, we must provide avenues for landowners to cope with lateral erosion that may threaten their property. For example, incentives such as purchasing conservation easements or sloughing bank easements on private lands would provide monetary reimbursement to landowners affected by bank erosion (Piegay et al. 1997).

Bank stabilization will continue until more stringent policies are adopted to limit such projects. In the interim, educating the public concerning the importance of fluvial processes to channel integrity and biological community structure should be undertaken. Determining and ameliorating the watershed-level causes of elevated erosion rates resulting in rapid channel migration would provide a more long-term solution than the current short-term practices of "repairing" (i.e., applying riprap) individual problem sites.

Resource managers will continue to struggle with the paradox of allowing natural fluvial processes and protecting private property and public infrastructure from those same processes.

As fishery managers, we need to recognize, and educate others, that lateral streambank erosion is a natural process that must be allowed to occur in many stream types (Rosgen 1994; Heede 1986). In a survey of streams in Wyoming, Idaho and Utah, meandering stream types were the predominant pattern (Leopold 1994). In addition, most valley bottom stream types that have the greatest tendency to migrate laterally lie within developed corridors and private property. In addition, if these same streams are not allowed to migrate laterally they may not provide high quality salmonid habitat. Interacting with the public and informing floodplain landowners of the risks associated with floodplain development will promote an appreciation for natural river processes and rivers in a natural condition. In the interim, resource managers will continue to struggle with the paradox of allowing natural fluvial processes and protecting private property and public infrastructure from those same processes.

Acknowledgements

Montana Fish, Wildlife and Parks, Montana Power Company, and the Bureau of Land Management, Missoula Field Office provided funding for this project. Comments by M. Marler, G. Mendel, A. Zale, and two anonymous reviewers improved the quality of earlier manuscript drafts.

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