PROJECT REPORT

Placing Riffle Formations to Restore Stream Functions in a Wet Meadow

by Alvin L. Medina and Jonathan W. Long

Natural materials and knowledge of natural stream processes are used to develop a cost-effective means of restoring a montane wet meadow stream.

Many mountain meadows in the southwestern United States have been eroded and dewatered by channel downcutting—an action that threatens trout fisheries, induces changes in vegetation, and can even cause perennially flowing streams to go dry (Heede 1986, Rosgen 1996). Restorationists seeking to restore channel stability and fish habitat in these riparian systems need to understand underlying geomorphic processes (Kondolf 2000), especially the role of pool-riffle sequences in maintaining dynamic equilibrium of stream channels (Dolling 1968, Yang 1971, Heede 1986).

While many stream rehabilitation efforts focus on modifying riffle or pool features (FISRWG 1998), systematic evaluation of most techniques has been limited (Kauffman and others 1997). Rock structures have been used to restore degraded riparian areas by halting further incision (DeBano and Heede 1987) and by reconnecting incised channels to their former floodplains (Rosgen 1997). Other approaches have favored plugging the degraded channel and redirecting flows into a newly constructed one (Rosgen 1997, Jemison and Neary 2000). Artificial riffles have also been used to enhance aquatic habitat, particularly in Europe, by providing substrates for spawning (Brookes 1987, Leopold 1994).

In this article, we describe a joint effort by the Rocky Mountain Research Station (RMRS) of the U.S. Department of Agriculture Forest Service and the White Mountain Apache Tribe to develop techniques that are cost-effective and emulate natural processes for restoring riparian wetlands in the White Mountains of Arizona. We are pleased to report that we have been able to build low-cost, in-stream riffle formations, using natural materials and processes, to restore degraded streambanks and enhance trout habitat and meadow vegetation.

Study Site

Pacheta Creek is a tributary of the Black River in the southeastern corner of the White Mountain Apache Reservation in east-central Arizona (Figure 1). A perennial stream, it has a typical low flow of 1.1 ft^3/sec (0.03 m^3/sec) and an estimated bankfull flow of 35.3 ft^3/sec (1 m^3/s), both of which are comparable to other mountain streams (DeBano and Heede 1987). Although high-intensity storms occur occasionally during the summer monsoon, the stream's peak flows occur principally from winter snowmelt across its 2.8-mi^2 (7-km^2) drainage area. At an elevation of 8,938 ft (2,725 m), the stream flows from a narrow canyon into a broad (820-3,280 ft [250-1,000 m]) wet meadow, known as Pacheta Cienega. This meadow reach harbors a robust population of non-native brook trout (*Salvelinus fontinalis*) (Rinne 2000), and is located at the transition from steeply sloping silicic rocks to flat-lying basalt flows (Merrill 1974). This geologic transition coincides with a shift

Ecological Restoration, Vol. 22, No. 2, 2004 ISSN 1522-4740 E-ISSN 1543-4079

in soil type from a gravelly loam to a dense clay loam (USDA SCS and USDI BIA 1981). The susceptibility of this reach to degradation reflects the tenuous equilibrium between the gravel bedload derived from the coarse-textured silicic volcanics and the fine-textured soils of the meadow.

Assessing the Degradation

In 1995, we observed that the channel had begun to downcut 590 feet (180 m) downstream from a culverted road crossing. Most of the gravels along the bed in this reach had washed away and the streambanks were sloughing into the stream. After 558 feet (170 m) of instability, the channel leveled out (less than 0.5 percent slope) into a flat, marshy area where the eroded sediments were depositing.

The streambanks were dominated by native graminoids, including blister sedge (*Carex vesicaria*), Nebraska sedge (*C. nebrascensis*), silvery sedge (*C. canescens*), woolly sedge (*C. lanuginosa*), Baltic rush (*Juncus balticus*), tufted hairgrass (*Deschampsia caespitosa*), meadow barley (*Hordeum brachyantherum*), and alpine timothy (*Phleum alpinum*). However, Kentucky bluegrass (*Poa pratensis*), an exotic perennial and an undesirable species for streambank protection (Medina 1996), had encroached on drier areas.

We attributed channel downcutting and widening to direct and indirect effects of use by elk and cattle (Figure 1). Animal trampling had formed "ramps" along some streambank sections used as crossings, left hoof imprints in the stream bed, and created slump deposits in the channel—all of which produce turbulence and concentrate stream flows (Trimble and Mendel 1995). These direct effects induced erosion of gravel substrates that armored the bed. The erosion scoured pools, widened the channel, lowered the water below the overhanging banks, and exposed plant roots. These geomorphic changes caused the meadow to become drier, which, in turn, favored the expansion of shallow-rooted graminoids, such as Kentucky bluegrass.

Starting in late 1995, the Tribe addressed the immediate cause of degradation by modifying livestock rotations across the landscape and by fencing this site to exclude livestock. Tribal hydrologists directed a project to enlarge the capacity of the culvert crossing to facilitate passage of bedload. However, drought conditions in 1996 constrained the growth of stabilizing vegetation and encouraged elk to feed and walk along the unusually shallow stream. Where the channel was becoming incised and unarmored, an additional 4 to 8 inches (10 to 20 cm) of downcutting occurred by 1997.

Figure 1. July 1997. Pacheta Creek at mid-point of treated reach, prior to restoration treatment. Note low level of water relative to banks, undermining of banks, and animal ramp in the left foreground. *Photo by Jonathan Long*

Riffle Formation Technique and Implementation

Geomorphologists recognize that incision of stream channels can be countered by dissipating the erosive power of the stream. We use the term "riffle formation" to describe composites of rock materials that are 1) sorted, with finer gravels placed above larger rocks that form the bottom layer at the downstream end; 2) packed down, with a dip to center flows in the channel; and 3) reinforced with sedge transplants (Figure 2B). Placement of riffle formations serve to dissipate energy by increasing the undulation of the channel bed, increasing the roughness of the channel, and spreading high flows into the floodplain. It is also possible to dissipate stream energy by increasing the meandering of the existing channel or by carving a new, more sinuous channel. However, in observing reference meadow sites, we found that channel sinuosity varies considerably, often reflecting changes in soil composition. Rather than laterally eroding or excavating the meadow's highly developed soils to form a more sinuous channel, we decided to use the riffle formation method because it uses commonly available rock materials to reestablish vertical stability within the existing channel pattern.

After comparing morphological data from two other meadow sites, we designed the treatment for Pacheta Creek. We quickly recognized that we would have to bring in riffle-forming materials because, although the bedload of Pacheta Creek was dominated by fine gravels, this natural source was insufficient to replace the coarse gravel substrates that had protected the channel bed from erosion.

To emulate natural formations, we studied stable reference sites to determine the location, length, height, and spacing of riffle formations in relation to stream gradient, soil characteristics, and substrates.

We also examined the incised streambanks of Pacheta Creek to locate gravel lenses that revealed the locations of former riffles. We marked starting and ending points for new formations at remnant riffle locations and above and below animal crossings (Figure 2A). This procedure produced an overall spacing between riffles of about four to seven bankfull widths, which is consistent with natural riffle sequences (Leopold and others 1964, Keller and Melhorn 1978).

Placement of the formations took one day of intensive labor. A Tribal enterprise delivered 16 tons (14.5 metric tons) of large gravels and small cobbles (1-5 inches [25-125 mm]) to the site. A work crew consisting of Tribal staff, RMRS scientists, and participants in the Tribe's summer youth environmental program transported the rock materials to each riffle site using wheelbarrows and a small trailer. Workers placed the rocks at 25 riffles spaced along 558 feet (170 m) of the degraded reach. Each formation averaged 7.9 feet (2.4 m) in length. Some workers raked and stomped the rocks into the bed and under the banks to keep flows centered through the riffles. Meanwhile, others cut plugs of sedges from wet areas in the meadow and placed them among gravels along the sides of the riffles. The purpose of transplanting was to stabilize the riffles with a living fabric and to revegetate bare areas along the streambanks.

In a stable meadow ecosystem, bankfull designates the level at which a stream can access its floodplain. We measured the height of bankfull in the stable section of Pacheta Creek and in comparable streams to be about 8 inches (20 cm) above base flows. Using these data, we placed the riffle formations so that the water level rose to within 8 inches of the top of the banks (Figure 2C).

We had also observed that water flowing over riffles in our reference streams was relatively quiet. This auditory clue helped workers build the riffles, since riffles that were built too high produced gurgling noises from the rapid flow of water over the formations. Workers repacked and raked the rocks toward the banks until the gurgling sounds subsided, indicating reduced velocities. Through an iterative process, we added rocks to raise riffles that became submerged as new ones were placed, until each riffle was at the desired height relative to the preceding and succeeding ones.

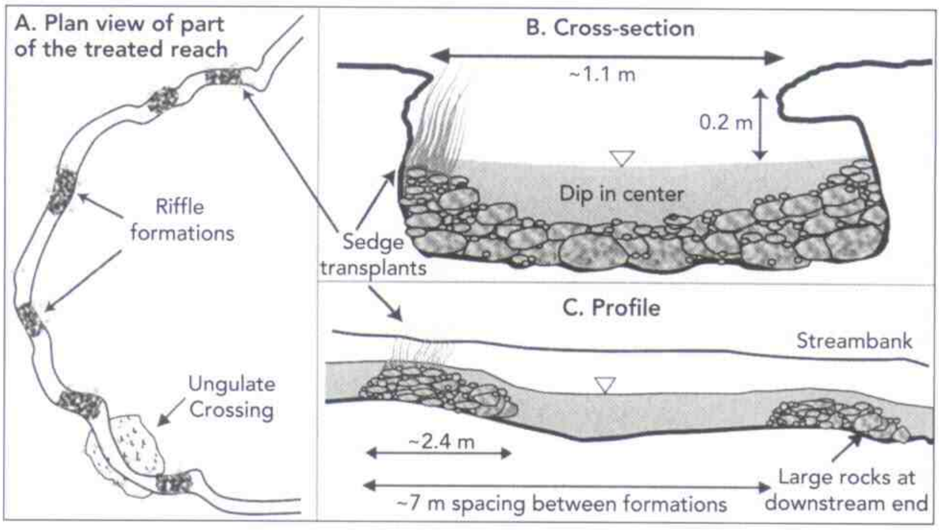

Figure 2. Plan view (A), cross-section (B), and profile (C) of typical reaches treated with riffle formations.

Analysis of Longitudinal Profiles

We profiled the stream channel at Pacheta Cienega using a laser level in July 1995 (when downcutting was first diagnosed), in July 1997 (prior to riffle placement), in October 1997 (after initial riffle placement), in July 1998, and in July 2000. We recorded bed elevation, thalweg water depth (the depth at the lowest point across the stream), and mean water depth in these surveys. From 1995 to 2001, we periodically sampled channel substrates using pebble counts (Bevenger and King 1995) along 40-m reaches in both the stable and the downcutting sections.

We used graphical analysis techniques to evaluate changes in channel morphology during the monitoring period. We entered the longitudinal profile data into a database, and then we used linear interpolation between measured points to compare changes in bed elevation and water depth through time. We estimated changes in bed material volume by multiplying the average difference in channel bed elevation by the length and average width of the reach. We calculated the absolute value of the deviations from the average slope to measure bed undulation (Madej 2001). To objectively identify pools and riffles, we calculated the differences in elevation between points along the profile and designated changes in bedform wherever a difference was greater than 0.75 times the standard deviation of the differences (O'Neill and Abrahams 1984).

Results and Discussion

We found that the increased height of the riffles reduced the average distance from the streambed to the bank in the most degraded reach by one-third, from 25 to 18 inches (63 cm to 45 cm) (Mann-Whitney U test, $p < 0.001$), which was a primary objective of the treatment. The riffle formations also increased average channel bed undulation, as measured in terms of absolute deviations from the average slope of the channel (Figure 3). The potential to increase the amplitude of bedforms is limited by the stream's tendency to smooth out riffles that are too high. However, the created formations appear to be within the tolerance of the channel, since bed undulation has not changed appreciably since they were placed (Figure 3). We also used the differencing technique to determine that the enhancement of pools and riffles did not produce much change in the percentage of pools (Table 1).

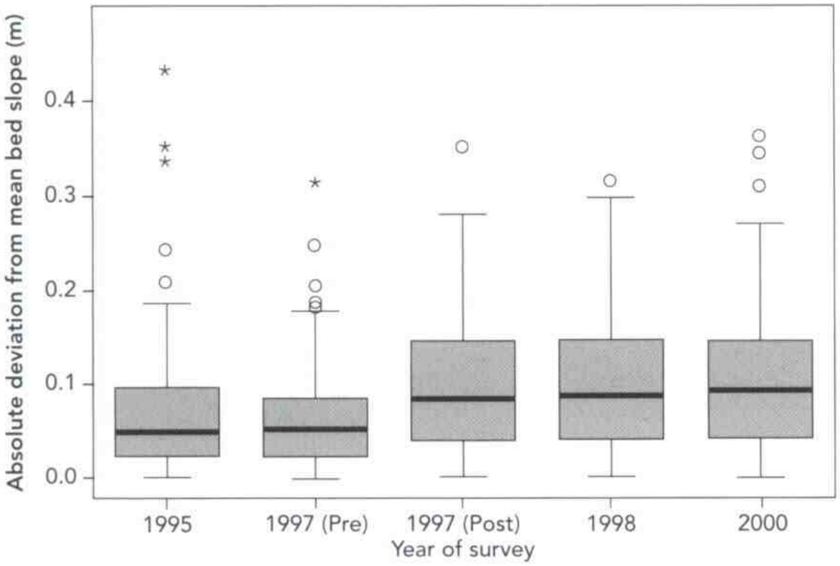

Figure 3. Channel bed undulation, as shown by boxplots of absolute deviations from the average bed slope (m). Median undulation (central bars) increased after riffle treatment in 1997 and remained stable through 2000.

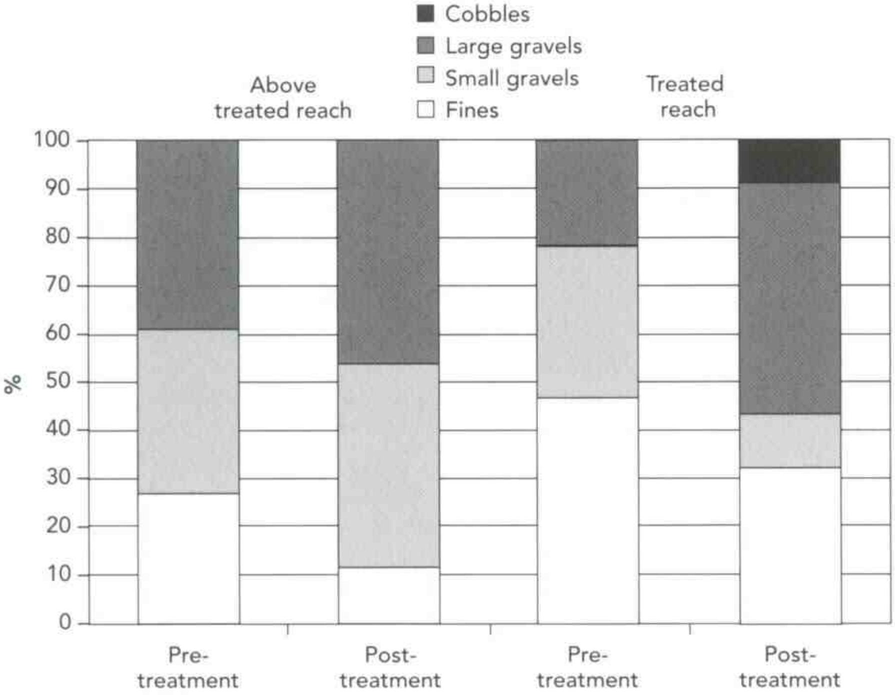

Figure 4. Zigzag pebble counts of the bed material pre- and post-treatment, both above and within the treated reach, show the distribution of different size materials. The cobbles and large gravels of the riffle formations supplanted the fine hardpan in the treated reach, while small and large gravel deposited above the treated reach.

While about 283 ft^3 (8 m^3) of bed material had been lost between July 1995 and July 1997 due to downcutting (Table 1), the installation of riffle formations replaced a significant amount of those materials. During the spring runoff in 1998, the heights of the riffles decreased while their lengths increased as some of the gravels slid into the pools immediately downstream. Later that year, we augmented some riffles that had sunk below their prescribed height and, in 1999, we placed large, angular cobbles on the downstream end of formations. With these changes, the bed regained nearly all of the material lost through the treated reach from its low in July 1997 (Table 1). Minimal changes in the longitudinal profile occurred between 1998 and 2000, indicating that the modifications to the channel bed had become stable.

Although streams generally rearrange gravels placed to form riffles (Brookes 1997), initial riffle shifting in this project may have been exacerbated by our use of rocks that were relatively homogenous in shape and size. As Leopold (1994) pointed out, and we now confirm, substrate heterogeneity helps to maintain a pool-riffle pattern. The combination of adding larger, angular rocks as well as the stream's incorporation of fine gravels from its natural bedload has increased the heterogeneity of substrates and reduced the amount of clay hardpan. As shown in Figure 4, coarse substrates have increased in the treated reach from 54 percent in 1995 to 68 percent in 2001 (Chi-square test, $p = 0.03$). Furthermore, changes in streambed composition have extended to the reach immediately upstream of the formations, where we measured an increase in coarse substrates from 73 percent in 1995 to 88 percent in 2001 (Chi-square test, $p = 0.006$) (Figure 4).

Capturing fine gravels in the bedload that would have been exported from the reach under pre-treatment conditions provides two important benefits. First, the fine gravels have filled in spaces between the larger substrates, reinforcing the stability of the formations. Second, the fine gravels lie in the size class (0.16-0.64 inches [4-16 mm]) that is optimal for trout spawning (Rinne 2000). Although gravel placement can be susceptible to infilling with fine sediments (Rosgen 1996), the bedload at this site is relatively coarse, and aquatic plants have been able to colonize the fine particles that are trapped on the channel margins.

Another important effect of the riffle formations was to increase the average thalweg water depth (Table 2). The depths

Table 1. Changes in channel morphology measured through longitudinal profile surveys of the entire treated reach from 1995 to 2001.

Survey Date	Change in bed material volume (m³) from previous survey	Net change in bed material volume (m³) since 1995	Percent pool (determined by bed form differencing)
1995	—	0	54
July 1997	-8.0	-8.0	63
October 1997	+2.8	-5.2	57
1998	+3.2	-2.0	50
2001	+1.4	-0.6	55
Overall Change		-0.6	+1

Table 2. Means and standard deviations of thalweg depth (cm) of pools, riffles, and overall reach before and after treatment.

Survey Date	Pool Depth		Riffle Depth		Overall Depth	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
July 1997	26.8	12.0	10.0	5.2	19.7	11.0
October 1997	36.6	13.1	17.3	10.8	28.2	15.5
1998	30.5	10.9	16.9	8.8	23.8	12.0
Change 97-98	3.7		6.9		4.0	
% Change 97-98	14.0		69.0		20.0	

of both pools and riffles increased because the formations raise the overall water level and are shaped to center flows mid-channel and away from the streambanks. As the formations raised water levels in riffles and pools, they also expanded in-stream habitat available to trout. Within the past three years (1999-2002), we, as well as anglers probing the site, have observed numerous trout swimming in the deepened pools. The formations also improved trout habitat by increasing the availability of wetted gravel substrates occupied by macro-invertebrates. This reflects other findings that artificial riffles can greatly increase benthic organisms (Gore and others 1998).

In terms of vegetation, the higher water levels along the channel have allowed the sedge transplants to thrive and revegetate former animal crossings and eroded banks (Figure 5). The addition of sedge transplants to the riffle formations has increased channel roughness and helped to bind the formations to the bank. The heightened riffles disperse flows onto the banks and into the meadow during spring floods. In addition to dissipating stream energy, the riffle formations have re-armored much of the bed, rendering it less susceptible to erosion. The treatment has also helped to reduce animal damage to the channel, since elk cross over the more resistant riffles. Furthermore, the treatment has improved the aesthetics of the meadow by replacing the pockmarked hardpan with an attractive mixture of variegated substrates.

Conclusions

Five years after the initial treatment, the riffle formations have proven to be a sound approach for restoring high-value pool-riffle systems where natural bedloads are insufficient to replace riffle materials lost to streambed erosion. In contrast to methods that require soil disturbance, this technique avoids the risk of increased sedimentation downstream. However, this treatment should be applied only in conjunction with treatment of the causes of degradation, which may include improperly designed road crossings and overuse by animals.

While gravel and rock formations have been used to restore degraded streams, this approach is distinctive because of its adaptive nature and the integration of plants and heterogeneous substrates to form the riffles. While the placement of the formations fit with empirically determined patterns, the stream itself suggested the location and heights for individual riffles. As the stream responded to the treatment by reshaping some of the formations, we added larger substrates to step down the steeper gradient sections.

The advantages of this technique for wet meadow restoration are its low cost ($500 for the rock and a few days of donated labor), its use of naturally occurring materials, and its lack of reliance on heavy equipment for installation. While the use of heavy equipment would be more cost-effective in situations requiring greater amounts of rock, the ability of manual laborers to properly sort and pack the riffle formation materials and integrate the sedge transplants into the formation should not be underestimated.

Finally, although it is a structural intervention, the riffle formation technique promotes stream evolution through natural processes. Although a single large structure could also prevent downcutting, multiple small structures are more effective because they re-create the natural geomorphology of the channel (Heede 1986, Rosgen 1997). Furthermore, using multiple small structures allows a wider margin for error in placement and allows the stream to rearrange the formations as it reestablishes geomorphic equilibrium. The formations can easily be modified by adding or removing substrates of different sizes. Therefore, we recommend reexamining the formations following high runoff events to ensure that they are functioning as desired and to allow for such adjustments if needed. For these reasons, the riffle formation technique provides an effective, adaptive approach to treating wet meadow degradation.

Building upon our experience at Pacheta Cienega, we have subsequently treated sites with moderate gradients (about 2 percent) by forming riffle steps composed of substrates ranging from small boulders to fine gravels. These formations perform similar geomorphic functions as log steps (Debano and Heede 1987), but with less risk of failure and need for maintenance.

ACKNOWLEDGMENTS

The authors wish to thank the White Mountain Apache Tribe and its members who imple-

Figure 5. July 2001. Pacheta Creek at mid-point of treated reach, after restoration treatment. Note height of water relative to banks and growth of sedge transplants across formerly bare ground. *Photo by Alvin Medina*

mented this restoration project, permitted the publication of these findings, and continue to demonstrate leadership in the ecological restoration of their ancestral homeland.

REFERENCES

Bevenger, G.S. and R.M. King. 1995. A pebble count procedure for assessing watershed cumulative effects. U.S. Department of Agriculture Forest Service, Rocky Mountain Forest and Range Experiment Station, Research Paper RM-RP-319.

Brookes, A. 1987. Restoring the sinuousity of artificially straightened stream channels. *Environmental Geology and Water Science* 10(1):33-41.

DeBano, L.F. and B.H. Heede. 1987. Enhancement of riparian ecosystems with channel structures. *Water Resources Bulletin* 23(3):463-470.

Dolling, R.K. 1968. Occurrence of pools and riffles: An element in the quasi-equilibrium state of river channels. *Ontario Geography* 2:3-11.

Federal Interagency Stream Restoration Working Group (FISRWG). 1998. Stream corridor restoration: Principles, processes, and practices. Washington, D.C.: The Federal Interagency Stream Restoration Working Group. GPO Item No. 0120-A; SuDocs No. A 57.6/2:EN 3/PT.653.

Gore, J.A., D.J. Crawford and D.S. Addison. 1998. An analysis of artificial riffles and enhancement of benthic community diversity by physical habitat simulation (PHABSIM) and direct observation. *Regulated Rivers: Research and Management* 14:69-77.

Heede, B.H. 1986. Designing for dynamic equilibrium in streams. Paper No. 86004. *Water Resources Bulletin* 22(3).

Jemison, R. and D.G. Neary. 2000. Stream channel designs for riparian and wet meadow rangelands in the southwestern United States. Pages 305-306 in U.S. Department of Agriculture Forest Service, Proceedings of land stewardship in the 21st century: The contributions of watershed management, RMRS-P-13.

Kauffman, J.B., R.L. Beschta, N. Otting and D. Lytjen. 1997. An ecological perspective of riparian and stream restoration in the western United States. *Fisheries* 22(5):12-24.

Keller, E.A. and W.N. Melhorn. 1978. Rhythmic spacing and origin of pools and riffles. *Geological Society of America Bulletin* 89:723-730.

Kondolf, G.M. 2000. Some suggested guidelines for geomorphic aspects of anadromous salmonid habitat restoration proposals. *Restoration Ecology* 8(1):48-56.

Leopold, L.B. 1994. *A view of the river*. Cambridge, Massachusetts: Harvard University Press.

Leopold, L.B., G.M. Wolman and J.P. Miller. 1964. *Fluvial processes in geomorphology*. San Francisco: W.H. Freeman.

Madej, M.A. 2001. Development of channel organization and roughness following sediment pulses in single-thread, gravel bed rivers. *Water Resources Research* 37(8): 2259-2272.

Medina, A.L. 1996. Native aquatic plants and ecological condition of southwestern wetlands and riparian areas. Pages 329-335 in Proceedings of the symposium on desired future conditions for southwestern riparian ecosystems: Bringing interests and concerns together. U.S. Department of Agriculture Forest Service, Rocky Mountain Forest and Range Experiment Station General Technical Report 272.

Merrill, R.K. 1974. The late Cenozoic geology of the White Mountains, Apache County, Arizona. Ph.D. dissertation, Arizona State University.

O'Neill, M.P. and A.D. Abrahams. 1984. Objective identification of pools and riffles. *Water Resources Research* 20:921-926.

Rinne, J.N. 2000. Effects of substrate composition on Apache trout fry emergence. *Journal of Freshwater Ecology* 16(3):355-365.

Rosgen, D.L. 1996. *Applied fluvial geomorphology*. Pagosa Springs, Colorado: Wildland Hydrology.

__. 1997. A geomorphological approach to restoration of incised rivers. Pages 12-22 *in* S.S.Y. Wang, E.J. Langendoen and F.D. Shields, Jr. (eds.), Proceedings of the conference on management of landscapes disturbed by channel incision, May 19-22, 1997. Oxford, Mississippi: The Center for Computational Hydroscience and Engineering, University of Mississippi.

Trimble, S.W. and A.C. Mendel. 1995. The cow as a geomorphic agent: A critical review. *Geomorphology* 13:233-253.

U.S. Department of Agriculture Soil Conservation Survey and U.S. Department of the Interior Bureau of Indian Affairs (USDA SCS and USDI BIA). 1981. Soil Survey of Fort Apache Indian Reservation, Arizona. U.S. Government Printing Office 235-991/102.

Yang, C.T. 1971. Formation of riffles and pools. *Water Resources Research* 7:1567-1574.

Alvin L. Medina and Jonathan W. Long are research ecologists at the Rocky Mountain Research Station, 2500 S. Pine Knoll Dr., Flagstaff, AZ 86001, 928/556-2180 and 928/556-2181, Fax: 928/556-2130, almedina@fs.fed.us and jwlong@fs.fed.us.