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FINE-GRAINED BED PATCH RESPONSE TO NEAR-BANKFULL FLOWS IN A STEP-POOL CHANNEL

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ABSTRACT: Fine-grained bed patches were monitored in a representative step-pool channel in the Arkansas Ouachita Mountains to assess their response to near-bankfull streamflow events. These patches are small, relatively well-sorted bed areas predominantly composed of gravel-size and smaller grains. They occupy 5.2 and 4.1% of the active and bankfull channel areas, respectively, over a 100-m study reach. During each of five simulated flow events with peak discharges ranging in size from 0.25 to 1.34 m^3/sec (1.0- to 1.6-yr return periods), 80% or more of the patches scoured or filled. Patch response frequency shows no difference between patch types, but does vary between hydraulic unit types. Patches show net aggradation in response to all events with fill volumes being two or more times greater than scour volumes. Patch response magnitude appears to vary somewhat between patch types, but not between hydraulic unit types. Both net volume and net depth change vary directly with peak discharge magnitude. The predominance of fill even at flows somewhat above bankfull stage suggests that bankfull events may not be sufficient for maintaining channel form in Ouachita step-pool channels.
KEY TERMS: fine-grained patches, step-pool channels, scour and fill processes, sediment storage

INTRODUCTION

Distinct, surficial bed areas where grain sizes are better sorted and substantially smaller than the channel median size are common within step-pool channels in the Ouachita Mountains of Arkansas. They occur as isolated, relatively small areas or "patches" with particle sizes typically between 0.062 and 64 mm. Such patches have been noted before in step-pool channels elsewhere (Laronne and Carson, 1976, Kondolf and others, 1991). The segregation of some gravel-bed channels into patches of differing grain size is receiving increasing study (e.g., Lisle and Madej, 1992, Paola and Seal, 1995), and this work suggests that fine-grained bed patches may be significant sources of bedload, especially during near-bankfull, peak-flow events.

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Fine-grained patches are investigated in this paper to determine how they react during near-bankfull flow events. Both their frequency and magnitude of response are examined. Furthermore, they are analyzed to determine if patch type or hydraulic unit type (both defined below) affect their response characteristics.

METHODS

A typical step-pool reach located within the Ouachita National Forest near Hollis, Arkansas was selected to study patch response. This reach is located on an unnamed tributary of Little Bear Cr and is hereafter referred to as Toots Cr. Vegetation is predominantly composed of a shortleaf pine (*Pinus echinata Mill.*) overstory and a mixed hardwood understory including white oak (*Quercus alba L.*), red oak (*Q. rubra L.*), and various hickories (*Carya* spp.) (Marion, 1996). Annual precipitation averages 130 cm and streamflows are ephemeral to intermittent. The catchment area above the study reach is 39 ha with an overall relief of 140 m and hillslopes ranging from 15% to 30%. Within the 100-m study reach, the channel has a weighted (by channel length) mean gradient of 8.8%. Banks are composed of mixed colluvial and alluvial deposits while surface bed material ranges from silts to boulders with an overall D_{50} of 56 mm.

Five individual flow events were studied with peak discharges ranging from 0.25 to 1.34 m^3/sec (1.0- to 1.6-yr recurrence intervals). The maximum and minimum event stages are shown in Figure 1 along with bankfull. Bankfull discharge was estimated to be 1.11 m^3/sec (1.4-yr recurrence interval) from channel features and computed hydraulic values. Flow events were created using a streamflow simulation system. Details on system design and operation are given in Marion and Weirich (1997). Events were produced on five consecutive days and sequenced so that Event 1 had the smallest peak flow while Event 5 had the largest.

The study reach was stratified into segments and each classified according to Grant and others (1990) hydraulic unit types (HUTs). Three different HUTs occur which contain patches: Cascade, Rapid, and Riffle types.

Patch scour and fill were measured using erosion pins installed in all 23 patches within the study reach. One pin was installed in the bed approximately in the center of each patch. A patch was defined to be greater than 0.3 m^2 in surface area and have at least 80% of its grains less than 64 mm. These criteria are based upon minimum area and grain size compositions observed for patches within the study reach. Visual inspections with only limited measurements were used to determine compliance with these criteria. After each event, all pins were measured to the nearest millimeter and reset flush with the bed surface.

Each patch was classified using the following type:

- Boulder shadow: Located adjacent to boulder or boulder group (but not within a pool).
- Lateral: Located along active channel margins.
- Pool: Located within bed depression with local negative slope.

Boulder shadow patches were first identified by Laronne and Carson (1976). Lateral patches differ from Boulder Shadow patches in that no boulder or other obstruction is located immediately adjacent to them.

Sediment erosion and transport were also monitored elsewhere using a variety of

methods. Erosion pins were installed in each of the six sites where soil material or bank deposits were exposed. Cross sections were installed within three different HUT segments. Seventy-three, bed clasts between 16 and 256 mm were randomly selected, painted white, and re-installed within the study reach. A bedload trap spanning the entire bed was installed at the downstream end of the study reach. All devices were measured prior to Event 1 and after each subsequent event. The channel was also visually inspected at the same times to identify any localized changes in erosion or storage.

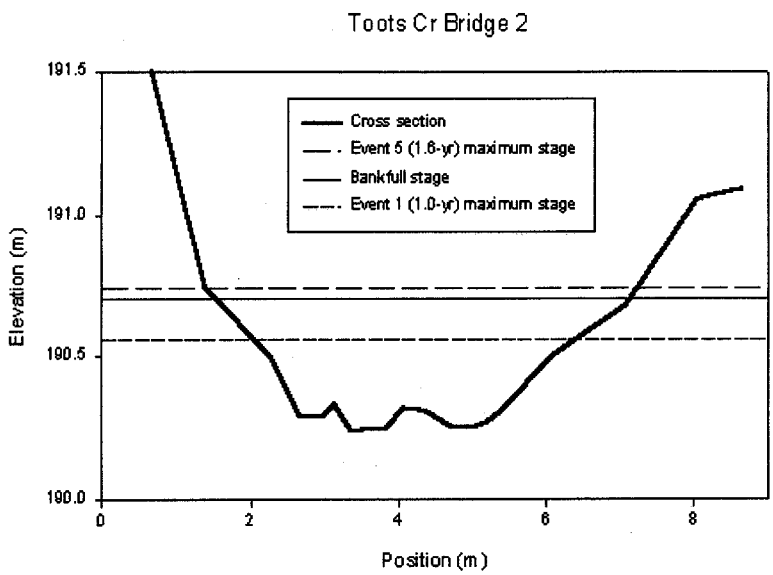

Figure 1. Comparison of maximum and minimum event stages with bankfull stage at Toots Cr. Bridge 2.

RESULTS

Fine-sediment patches occupy 5.2% and 4.1% of the active and bankfull channels, respectively. Although only measured prior to Event 1, all patches were visually inspected after each event and none of the patch areas appeared to change appreciably. Boulder Shadow, Lateral, and Pool patch types occur with a relative frequency of 5:2:1 for the 23 patches observed. Size and shape characteristics do not vary much between patch types. Over 90% of patches are less than 1.5 m^2 in area. Flow orientation is predominantly parallel to the patch long axis for all types.

Patches show some clear differences between HUTs. Patch occurrence frequency is similar for Riffle and Rapid sections, while Cascade patches occur approximately three times less often. Patch type differs, too, with Pool types occurring more often in Cascade units, and Lateral or Boulder Shadow types occurring more in Riffle and Rapid units. Patch size differs between HUTs in that Riffle patches are longer and have greater area than those in either Rapids or Cascades. Patches do not differ in width, shape, or flow orientation between HUTs.

Response Frequency

Response Type by Discharge

Bedload data indicates that the grain sizes corresponding to those predominantly occurring in patches were frequently transported in all five events. Maximum bedload sizes from trap and tracer samples are in the 64-128 mm size range during all events except 4 where the maximum is in the 128-256 mm range. Grain sizes ≤64 mm make up 32-88% of all bedload moving during all five events.

Patch response frequency is fairly constant over the range of peak flows studied (see Figure 2). Approximately 80% or more of all patches respond during each event with all patches showing at least one response over the five events. Peak discharge increases in successive events do not appear to greatly affect the number of patches which respond, as indicated by the relative consistency in this number for each event.

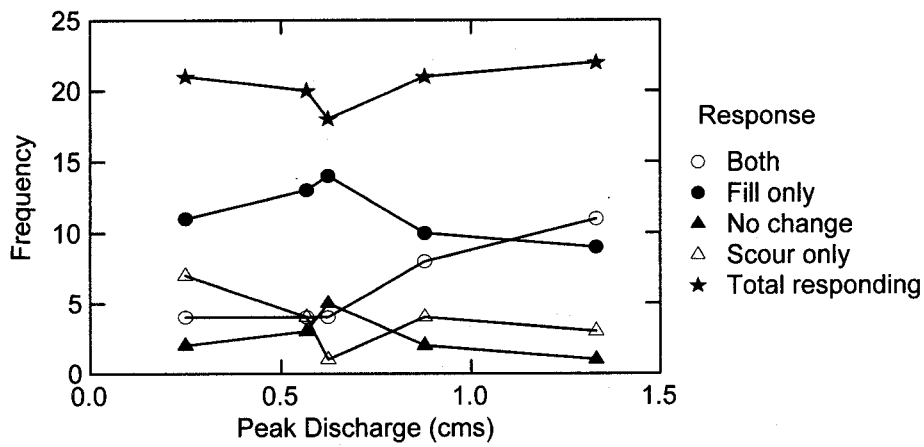

Figure 2. Response type frequency by event peak discharge for fine-grained bed patches.

The number of patches which only fill is consistently greater than those which only scour in all events (see Figure 2). It is twice the number for scour-only patches in all events except Event 1 and is greater than those which both scoured and filled in all except Event 5.

Effect of Patch Type and HUT on Response Frequency

Patch response frequency is not affected by patch type. When patch response is simplified to just whether or not the patch changes, a Pearson Chi-square test indicates there is no important overall difference in response frequency between patch types ($P = 0.86$), rather that response frequencies are in line with the occurrence frequency of each patch type. This holds true for each separate event as well (all $P > 0.20$).

Patch response does show some indications of varying between different HUTs ($P = 0.08$). Over all events, Cascade patches have fewer responses than expected, Rapid patches have more, and Riffle patches respond as expected. Event 5 (1.34 m^3/sec) accounts for most of this variance. While differences are not evident for Events 1-4 (all $P > 0.19$), they are very clear for Event 5 ($P = 0.03$). In Event 5, both Rapid and Riffle patches respond more often

than expected, and Cascade patches less often. However, individual event results are not conclusive due to the small sample sizes.

Volume Change

The net response of patches is to consistently aggrade over the range of peak flows studied. Net volume change is positive for all events indicating that patches fill more than they scour (see Figure 3A). Fill volumes are two or more times scour volumes for given peak discharges. Filling consistently occurred in 50% or more patches than scoured (see Figure 3B).

This net aggradation is primarily caused by the change in fill magnitude for individual patches, not by the change in patch response frequency or a change in scour volume. The frequency of patches filling does increase steadily with discharge (see Figure 3B). Note that the frequencies shown in Figure 3B differ from those in Figure 2. The former indicates the total number of patches which exhibited either scour or fill. For example, the 11 patches in Event 1 that scoured include 7 which scoured only and 4 which both scoured and filled (see Figure 2). The increase in individual patch fill volume has a much larger effect on total fill volume than does the frequency increase. Total scour volume is relatively constant over the discharge range used (see Figure 3A).

Change by Patch Type, HUT, and Discharge

The effects of patch type, HUT, and discharge on patch net volume change were tested using General Linear Model analysis within an incomplete block design with a two-way treatment structure and repeated measures (nomenclature after Milliken and Johnson 1984). While net volume change is primarily discussed below, the same findings and interpretations hold for patch depth change unless otherwise noted.

Net volume change is not affected in a general way by either HUT or patch type, but does seem sensitive to particular combinations of HUT and patch type. The overall HUT effect is very low ($P = 0.30$) and pairwise differences between HUTs (e.g., Cascade versus Riffle) are unremarkable (all $P > 0.50$). However, within a given HUT, pool patches do appear to be somewhat different from the other patch types. The differences between Lateral and Boulder Shadow patches within both Rapid and Riffle units are very small (both $P > 0.29$), but both appear to differ from Pool patches (both $P < 0.05$) within Riffle and Cascade units. Differences with Pools are not significant at the standard 0.05/2 level for a two- sided test, but would be at the 0.10/2 level. These tests indicate that Pools have the largest volume changes in all HUTs where they occur.

Discharge strongly influences the magnitude of patch changes. Net volume change shows a clear overall response of increasing positive values with increasing discharge ($P = 0.01$). The overall effect of discharge is even more pronounced for depth change ($P < 0.001$). The median depth response is shown in Figure 3C. Pairwise comparisons between successive events indicate that clear changes in patch response occur when discharge increases substantially. Depth change during Event 2 differs from that in Event 1 ($P = 0.02$). Event 2 and 3 changes do not differ ($P = 0.22$), but both are significantly smaller than the Event 4 depth change ($P = 0.002$ and 0.01, respectively). Event 4 and 5 differences are not significant at the 0.05/2 level ($P = 0.04$), but are close. In this case, Event 4 changes are larger than those in Event 5. Volume changes show the same pattern of differences, but have somewhat larger probabilities.

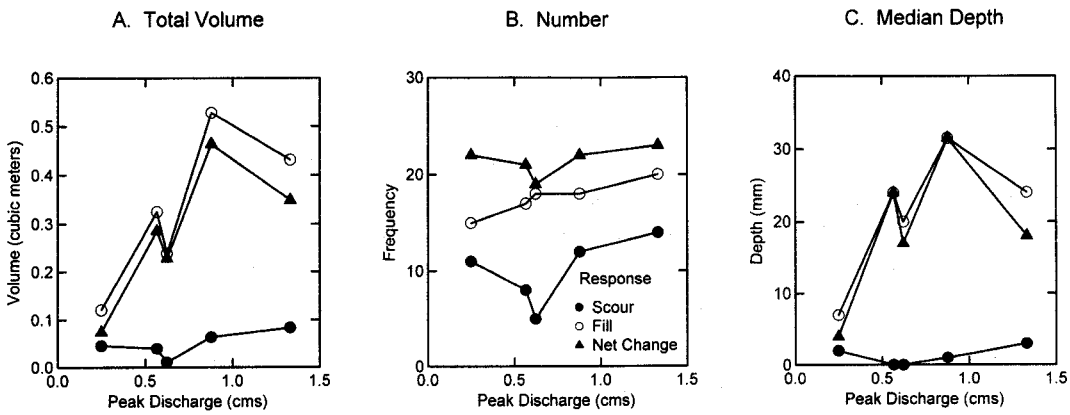

Figure 3. Patch response by event peak discharge.

Sources of Patch Sediment

The sediment which accumulated in these patches during the five events does not appear to come from any one particular source. The total volume change in bank erosion sites is 0.0006 m^3, or 2-3 orders of magnitude less than total patch volume change (see Figure 3). Of the six bank erosion sites, only two ever responded: one during all events, the other during just Event 5. The former site could easily have been classified as a bank patch as it occurs along the channel margin beneath an undercut bank area. The undercut bank did not appear to erode during any of the events, while the portion along the channel margin accumulated sediment in all except Event 1.

Patch sediment does not come from localized changes in channel shape or out-channel inputs. Cross-sectional area only changes significantly in two of the five events at the three cross sections monitored. These two significant changes occur at different locations and in different events. The percent change is 2% or less in both cases, with one location increasing and the other decreasing in area. Also, sediment release from coarse woody debris dams or step breakdowns did not occur as the former are absent within the reach and the latter did not occur. Lastly, because of the experimental controls imposed, no sediment was input from out-channel or upstream sources during any of the events.

DISCUSSION AND CONCLUSIONS

Fine-grained bed patches are important features of step-pool channels in the Ouachita Mountains. Bed patches act primarily as sediment sinks during events with peak discharges of less than 1.6-yr recurrence. Despite the relatively small grain sizes within patches, they do not appear to be the primary source of bedload during the events considered here. The sediment accumulating in patches must originate in part from elsewhere in the channel. Patch sediment cannot come from just patch sources because scour volumes are substantially less than fill volumes over the entire flow range (see Figure 3A). Bank erosion does not supply this additional sediment. Cross-section change is evident, but is inconsistent and seems insufficient to make up this difference. The degree of preferential deposition at patches may be such that

the small amount of scour which does occur in all other parts of the channel is predominantly dropped at these sites.

The pattern of net sediment accumulation in patches over the discharge range studied suggests that discharges greater than bankfull are necessary to maintain long-term channel form. Patch fill volume increases during flows from 0.25 to 0.88 m^3/sec (1.0- to 1.2-yr events, see Figure 3A). It declines during flows from 0.88 to 1.34 m^3/sec (1.6-yr), but still remains positive and over three times scour volume. Insufficient data exist to project the net volume trend beyond the 1.6-yr flow, but it does appear clear that the discharge needed to balance patch scour and fill is greater than bankfull. Maintaining channel form over periods of years to centuries requires that channel deposition in patches and other channel features be balanced by compensating scour, otherwise net aggradation will take place and significant morphologic changes will occur. There is no evidence to suggest that the study reach has either aggraded or degraded over the last several decades. Channel morphology and bed and bank compositions within the study reach are all very similar to those observed in most stable step-pool channels within undisturbed forest stands of the Ouachita Mountains. Thus, patch flushing seems to occur often enough that patches maintain their long-term size and composition characteristics. Data from these experiments suggests that such flushing occurs at flows greater than bankfull.

Kondolf and others (1991) document scour behavior in fine-grained, step-pool patches which also suggests that greater-than-bankfull events may be necessary to maintain patch form. They did not measure patch scour and fill directly, rather they monitored tracer-pebble (25.4 to 90.0 mm) displacement. They found that extensive scour of fine-grained patches occurred during a year which included a 7-yr peak flow, but little evidence of scour occurred after a dry year (65% of average runoff). Since patch volume or depth were not measured, its not certain whether or how these changed, but Kondolf and others results do add to the possibility that patch flushing and step-pool channel maintenance require greater-than-bankfull events.

The abbreviation of flow duration in all events except Event 1 may be a factor in causing the observed patch aggradation. The shortening was necessary in these events because the streamflow simulation system had insufficient capacity to fully replicate entire recession flow periods. Its occurrence reduced the time period over which the bed was exposed to flows less than the event peaks. Note that recession flow compression did not occur in Event 1, yet fill volume and median depth were still over twice those for scour volume and depth (see Figure 3). Nonetheless, the higher-magnitude discharges during recession flows in subsequent events did occur over much shorter time periods than typical of natural events. Such compression could have reduced sediment transport yields (i.e., increasing fill) of patch sediments whose relatively smaller sizes would have been most likely to move during these flows.

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REFERENCES

Grant, Gordon E., Frederick J. Swanson, and M. Gordon Wolman, 1990. Pattern and Origin of Stepped-bed Morphology in High-gradient Streams, Western Cascades, Oregon. Geological Society of America Bulletin 102:340-352.

Kondolf, G. M., G. F. Cada, M. J. Sale, and T. Felando, 1991. Distribution and Stability of Potential Salmonid Spawning Gravels in Steep Boulder-bed Streams of the Eastern Sierra Nevada. Transactions of the American Fisheries Society 120:177-186.

Laronne, J. B., and M. A. Carson, 1976. Interrelationships Between Bed Morphology and Bed-material Transport for a Small, Gravel-bed Channel. Sedimentology 23:67-85.

Lisle, T. E. and M. A. Madej, 1992. Spatial Variation in Armouring in a channel with high sediment supply. In: Billi, P.; Hey, R. D.; Thorne, C. R.; Tacconi, P. (eds). Dynamics of Gravel-bed Rivers. Chichester, UK: John Wiley: pp. 277-291.

Marion, Daniel A. and Frank Weirich, 1997. Simulating Storm Events. Environmental Testing and Analysis 6(4):15-16

Marion, Denise, 1996. Ordination of Woody Vegetation in a Ouachita National Forest Watershed. Unpublished research paper on file at USDA Forest Service, Forest Hydrology Laboratory, 1000 Front St, Oxford, MS 38655-4915.

Paola, Chris and Rebecca Seal, 1995. Grain Size Patchiness as a Cause of Selective Deposition and Downstream Fining. Water Resources Research 31(5):1395-1407.