PALEOHYDROLOGY OF POOL AND RIFFLE PATTERN DEVELOPMENT:

BOULDER CREEK, UTAH

by

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ABSTRACT

The low-flow channel morphology at Boulder Creek is characterized by a well-developed pool-and-riffle pattern. The riffles consist of accumulations of basaltic boulders deposited from upstream source areas during extremely large flows. Paleoflood water-surface profiles defined by highwater indicators such as slackwater sediments and silt lines indicate that discharges of up to $400 \pm 50$ cms have affected the lower reaches of this stream system. Stratigraphic relationships and archaeologic and radiometric age constraints indicate that at least four large-magnitude, low-frequency flow events have occurred within the last 500 to 1000 radiocarbon years B.P.

Step-backwater hydraulic reconstructions of these large flows suggest that the positions of the boulder-comprised riffles are controlled by spatial variations in large-flow stream power. Boulder deposition occurs where channel stream power drops below thresholds necessary for boulder transport. Reaches immediately upstream of canyon bends and constrictions, and downstream of canyon expansions are sites of large-flow stream-power minima. It is in the vicinity of these types of canyon geometries that the low-flow riffles are observed. Comparison of calculated stream power values and measured boulder sizes with established coarse-particle transport relationships indicates that a 400 cms flow is approximately the minimum discharge that has the competence to affect this pool-and-riffle pattern.
INTRODUCTION

Paleohydrologic techniques can be powerful tools for increasing our understanding of channel processes in certain types of fluvial environments. Paleohydrologic studies can provide information of the long-term flood history of a stream system; information that is invaluable to the planner or geomorphologist concerned about potential flooding. Hydraulic modeling of these flows can benefit planners, engineers, and fluvial geomorphologists in that it provides quantitative information about flow conditions that have been, or may be, experienced by a particular stream system. Applying these techniques from a geomorphological perspective to a small stream in southern Utah has allowed added insights into pool and riffle pattern development in canyonland streams.

Wolman and Miller (1960) proposed that the one to two year recurrence interval flow event is a primary agent of geomorphic work in fluvial systems. This concept has been amended by recent workers who have noted the potential for catastrophic response associated with large-magnitude, low-frequency, flooding. In certain physiographic environments, such as the American southwest, rare hydrologic events may be the dominant force in controlling various aspects of channel morphology (Stewart and LaMarche, 1967; Baker, 1977; Graf, 1979). While the effects of these large magnitude, low frequency events can be described readily, direct analysis and measurement of large flow channel processes is a difficult, if not impossible, endeavor. In addition, because direct stream flow observation records are usually
short with respect to the recurrence intervals of rare events, it is difficult to gain a proper perspective on how often these events may affect a fluvial system (Baker and others, 1979).

In certain settings geologic evidence can be used to not only analyze the end effects of catastrophic flooding, but also to investigate the nature of the processes controlling the resulting channel morphology. Bedrock stream systems commonly contain fine-grained sediments (slackwater sediments) that record floods of extreme magnitude. If these deposits represent several events and are datable, a flood chronology, sometimes spanning several thousands of years, can be developed (Baker and others, 1979; Kochel and others, 1982; Baker and others, 1983). Hydraulic modeling of floods represented by geologic evidence can lead to insights about the flow conditions associated with rare flow events and the related processes that may be important in controlling stream channel morphology. At Boulder Creek, southcentral Utah, analysis of sedimentologic evidence for large paleofloods allows for the evaluation of the relationship of a distinct pool and riffle pattern to large and rare flows.

BOULDER CREEK, UTAH

Boulder Creek (average annual discharge approximately 2.0 cms) drains 451 km² before joining the Escalante and subsequently, the Colorado Rivers (Fig. 1). The basin heads in Cenozoic basalts (McFall, 1979) that cap the 3400 m high Aquarius Plateau. 25 km downstream from the Plateau escarpment, at an altitude of 1800 m, the perennial stream becomes entrenched into massive Triassic-Jurassic Navajo Sandstone. Boulder Creek then flows in incised meanders with
FIGURE 1. Location map. The investigated reach consists of the 6.5 km of Boulder Creek immediately upstream of the Escalante River confluence.
steep, often vertical, canyon walls upwards of 100 m high. In some reaches the low-flow channel is bounded by bedrock walls on both sides, but more generally, heavily vegetated sandy flood deposits flank one or both banks of the stream. During floods, flow extends from wall to wall and stages are high relative to flow width (Fig. 2).

Within the incised portion of Boulder Creek, the low-flow morphology is characterized by a distinct pool and riffle topography established in the thin veneer of channel bottom alluvium (Figs. 3 and 4). The riffles are short reaches of relatively high water-surface slope where the stream flows over accumulations of Aquarius Plateau derived basaltic boulders. The pools are the intervening sandy-bottomed reaches of low water-surface slope that occur between these riffle dams. The basaltic boulders that comprise the riffles are large and apparently fluvially transported during large flows. Measured major axes of boulders in a few of the riffles exceed lengths of 2 m. The boulders are rounded and well sorted (Fig. 3), and the boulder accumulations occur some 25 to 30 kilometers from their Aquarius Plateau source area. These riffle characteristics generate some interesting questions regarding the development of Boulder Creek's pool and riffle pattern:

1. Considering the size of the riffle boulders, what are the magnitudes and frequencies of flows affecting this aspect of channel morphology?
2. With what specific flow (hydraulic) conditions are the boulder accumulations associated?
3. Can any general qualitative models be proposed that account for the positions of riffles in this type of fluvial system?
FIGURE 2. Typical cross-sectional geometry within the study reach.

The channel is constrained both vertically and horizontally by bedrock, resulting in relatively high depth-to-width ratios during large flows. Low-flow discharges are confined by heavily vegetated (willows and saltcedar) banks 0.5 to 2m high.
FIGURE 3. Typical pool and riffle sequence at low flow (discharge approximately 2.5 cms). Riffles are composed of basaltic boulders derived from the Aquarius Plateau.
FIGURE 4. Surveyed profile of low-flow water surface and channel bottom for the 0.6 km study reach upstream of the Escalante confluence. The low-flow water surface drops in a step-wise manner over the channel riffles. All the riffles are formed by basaltic boulder accumulations except for a bedrock riffle (not mapped) immediately downstream from boulder riffle 9.
In search of solutions to the above questions, a 0.6 km reach of lower Boulder Creek (immediately upstream from the Escalante confluence) was chosen for detailed study (Fig. 5). Work here included a survey of the channel and canyon floor, measuring and mapping riffles, and description and analysis of flood sediments preserved at several sites in the study area. In addition to the reach studied in detail, riffle positions were mapped for another 5.9 km upstream.

BOULDER CREEK FLOOD CHRONOLOGY

The first step in investigating the relationship of the Boulder Creek pool-and-riffle pattern to large-flow hydraulics is to determine the magnitudes of the largest flows that have affected this stream system. The paleoflood history at Boulder Creek is defined through the use of datable flood slackwater deposits and silt lines in conjunction with the U.S. Army Corps of Engineers HEC-2 Water Surface Profile computer program (Hydrologic Engineering Center, 1979).

FLOOD SEDIMENTS

Slackwater sediments have been successfully utilized as paleoflood highwater indicators to construct long-term flood frequency and magnitude relationships in Texas (Baker and others, 1979; Patton and others, 1979; Kochel and others, 1982), Northern Territory, Australia (Baker and others, 1983), and for the Escalante River of southcentral Utah (Webb and Baker, 1984). Slackwater sediments are silt- to sand-sized materials that accumulate rapidly from suspension at protected areas during large flow events (Baker and others, 1983). Areas of deposition usually occur at locales of flow separation, where highly sediment-charged waters are isolated to the sides of the high velocities and turbulence
FIGURE 5. Surveyed study reach. This reach was chosen because of
the presence of several sites of paleoflood highwater indicators
and a well defined pool and riffle sequence.
of the main flow. Sites behind bedrock spurs and up side canyons are especially conducive to slackwater sedimentation. Subsequent floods may be recorded at such sites either as superimposed sedimentary deposits, or as insets deposited against pre-existing flood strata. A given flood may produce either relationship depending on its stage in relation to the maximum elevation of older flood deposits. If conditions are favorable for preservation, the deposits may persist for several millenia (Baker and others, 1983). Dating (radiometric and/or archaeologic) of stratigraphic units within a sequence of flood sediments can lead to a paleoflood chronology and long-term flood frequency-magnitude relationships (Kochel and others, 1982; Baker and others, 1983).

Within the study reach at Boulder Creek, there are two multiple unit slackwater deposits (Sites Four and Six of Fig. 5). In addition to the slackwater sediments, there are vestiges of silt lines preserved along protected portions of some of the canyon walls (Sites One, Two, Three, Five, and Seven of Fig. 5). Radiometric and archaeologic age constraints suggest that these deposits represent at least a partial flood history for the last several hundred years.

LARGE FLOW EVENTS: SEDIMENTOLOGIC EVIDENCE AND AGE CONSTRAINTS

The site of greatest paleohydrologic utility is the well-preserved slackwater deposit of Site Four (Fig. 5). This deposit is in a small alcove located 55 m away from the main channel in a small tributary canyon (Fig. 6). Here, eight distinct sedimentologic units of Boulder Creek provenance (as opposed to sediments derived from the small tributary) were identified (Fig. 7). Each of these stratigraphic units
FIGURE 6. Slackwater deposit at Site Four. This site contains the record of four to eight Boulder Creek flood events (See Fig. 7 and Table 1.). All other flood evidence in the study reach is correlated to units preserved here. Local tributary sediments are also present here but are readily distinguished from Boulder Creek deposits on the basis of color and texture. Note trowel for scale.
FIGURE 7. Schematic diagram of the stratigraphic relationships at Site Four (sedimentologic descriptions in Table 1). Flood deposits have accreted vertically as well as laterally at this site. Radiocarbon analysis of transported organic material incorporated within one of the higher depositional units (D) has helped to constrain the ages of some of the flow events (Table 1). A. Front view. B. Side view. No horizontal scales.
A.

EXPLANATION:

- **R** BOULDER CREEKSEDIMENTS
- **G** TRIBUTARYSEDIMENTS
- **C** ROCKFALLBOULDERS
- **D** BOUNDARIESBETWEENDEPOSITS
- **E** REPRESENTATIVEOFINTERNALSTRATIFICATION

B.

SECTION A-A
may indeed represent discreet flow events; however, only those sedimentologic units that are separated stratigraphically by tributary sediments or that have been radiometrically determined to have different ages can be safely interpreted to be the result of separate floods, since individual flows are capable of several depositional episodes as stage waxes and wanes. The stratigraphic relationships and one radiometric date at this site indicate that these eight depositional units represent a minimum of three separate events on the basis of the above criteria (Fig. 7, Table 1). In addition, one other sedimentologic unit (F) is inferred to represent a separate event from those depositing the higher stratigraphic units (D and E). Evidence supporting this interpretation is a slightly younger radiocarbon date (not statistically significant), the large stage fluctuations that would be required if the flow depositing unit F was not independent of those depositing the higher units, and a slightly better preserved correlative silt line.

The sediments of Site Six (Fig. 5) are in a similar setting to Site Four; they were deposited in a small side canyon alcove approximately 60 m away from the main channel (Fig. 8). However, extensive bioturbation and stratigraphic complexity has somewhat obscured the flood deposit relationships, rendering this site less useful than Site Four for paleohydrologic analysis. However, radiometric analyses of transported organic debris in the stratigraphically oldest and youngest flood deposits yield ages of 540 ± 100 (A-4007) and 180 ± 50 (TX-5063) \(^{14}\text{C}\) yr BP, respectively, implying that this deposit repre-
TABLE 1. DESCRIPTIONS, POSITIONS, AND AGE CONSTRAINTS OF THE BOULDER CREEK FLOOD DEPOSITS AT SITE FOUR

<table>
<thead>
<tr>
<th>STRATIGRAPHIC UNIT</th>
<th>ELEVATION ABOVE DATUM (M)</th>
<th>DESCRIPTION</th>
<th>AGE CONSTRAINTS</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planar laminated sandy silt. Brown (7.5YR 5/4).</td>
<td>11.09</td>
<td>Stratigraphically oldest unit in the deposit.</td>
<td>Interpreted to represent a discreet flow event. Based on sedimentologic nature and position, may be correlative with the lower, older unit at Site Six.</td>
<td></td>
</tr>
<tr>
<td>Fine silt to silty-fine sand. Brown (7.5YR 5/4). Undulating laminations thicken (0-20m) and coarsen upwards. Lower and upper boundaries abrupt and plane.</td>
<td>11.63</td>
<td></td>
<td>Chronological position not known with certainty. If inset, could be associated with other events represented by deposits here. Therefore, cannot be delineated unequivocally as a discreet flow event.</td>
<td></td>
</tr>
<tr>
<td>Finely laminated sandy silt to silty-medium sand. Brown (7.5YR 5/4).</td>
<td>12.38</td>
<td>By stratigraphic position, younger than Unit A. If this deposit is inset into the local tributary sediments overlying Unit A, it can only be constrained as being older than Units F, D, E, F, and G. If Unit B is not inset into the local tributary sediments, but was accreted vertically, it is probably older than Units C and D.</td>
<td>Based on sedimentologic nature and position, may be correlative with the lower, older unit at Site Six. Therefore, cannot be delineated unequivocally as a discreet flow event.</td>
<td></td>
</tr>
<tr>
<td>Massive, brown (7.5YR 5/4) silty-fine to silty-medium sand.</td>
<td>13.09</td>
<td>By stratigraphic position, older than Units D, E, F, G, and H. Younger than Unit A. If inset, could be associated with other events represented by deposits here. Therefore, cannot be delineated unequivocally as a discreet flow event.</td>
<td>Bound above and below by tributary sediments. Therefore, regarded as representing a single flow event.</td>
<td></td>
</tr>
<tr>
<td>Massive pink (7.5YR 5/4) silty-fine to silty-medium sand. Some wavy lamina of finer-grained (coarse silt to fine silt) sediments within the lower 10cm paralleling the wavy, abrupt lower boundary.</td>
<td>12.09</td>
<td>Insert in Units D and E. Therefore constrained to be of equal age or younger with respect to Unit D. Younger than Unit C.</td>
<td>Bound below by tributary sediments, therefore regarded as representing a later event. Units D and E are at equal elevations and represent the largest flow(s) preserved in the geologic record.</td>
<td></td>
</tr>
<tr>
<td>Brown (7.5YR 6/4) laminated silty-fine-sand grading to silty medium sand. Laminations thicken and coarsen upwards. Deposit capped by 2mm of fine silt. Top boundary planar. Lower boundary abrupt and wavy.</td>
<td>11.95</td>
<td>Insert into Units A, B, and E. Therefore, of equal age or younger with respect to those deposits. Disseminated organics from a correlative deposit at Site Seven yield an age of 110,000 yr BP (A-4006).</td>
<td>Interpreted to represent an individual flow event from the flow(s) depositing Units D and E primarily on the basis of a slightly better preserved correlative silt line. In addition, large stage fluctuations would be required if Unit F was also deposited by the flow(s) depositing Units E and F.</td>
<td></td>
</tr>
<tr>
<td>Section collapsed before described.</td>
<td>11.50</td>
<td>Insert into Units F, G, and H. Therefore, of equal age or younger with respect to Unit F.</td>
<td>Lack of age constraints precludes delineating Unit G as a separate flow event.</td>
<td></td>
</tr>
<tr>
<td>Massive brown (7.5YR 6/6) silty-fine to medium sand. Abundant large organics debris in the top 5cm. Top boundary planar. Deposit lies on bedrock at the base of the alcove.</td>
<td>10.69</td>
<td></td>
<td>Lack of age constraints precludes delineating Unit G as a separate flow event.</td>
<td></td>
</tr>
</tbody>
</table>

*Boulder Creek deposits are readily distinguishable from the local tributary sediments on the basis of color and texture. Tributary sediments are redder (2.5YR) and coarser (coarse sand to gravelly and cobble coarse sand).

*Represents the elevation of the top of the deposit above the arbitrary datum.
FIGURE 8. Flood sediments at Site Six. Radiocarbon dates were obtained from organic flood debris at the indicated locations. Based on sedimentologic similarities, position, and radiometric ages, the uppermost deposit is correlated to Units D-E of Site Four, and the low, fine-grained deposit from which the $540 + 110$ $^{14}$C yr BP date was obtained is tentatively correlated to Unit A of Site Four.
sents at least a partial paleoflood record for approximately the last 500 years.

Silt lines are subhorizontal linear deposits of silt- and clay-sized particles that line some portions of the canyon walls. Presumably, these deposits are derived from the suspended load of the flooded stream, being left as the flood waters percolate into the permeable Navajo Sandstone. While silt lines are not normally datable, they serve as excellent paleostage indicators and are especially important defining paleoflood water-surface profiles. Within the Boulder Creek study reach, a prominent pair of silt lines is preserved at Sites Two, Three, and Seven. In addition, a single silt line is identified at Sites One and Five. Based upon their relative positions and timing, the upper and lower silt lines of the prominent pair are probably correlative to sedimentologic units D-E and to unit F of Site Four, respectively. The single silt line remnants at Sites One and Five are correlated, on the basis of their elevation above the channel bottom, with the highest stratigraphic units (D-E) at Site Four. At both of these single silt line locations, there are remnants of flood deposits at the approximate position where the lower silt line would be expected.

Some additional age constraints exist at Site Seven where both silt lines have been emplaced upon a panel of petroglyphs (Fig. 9), and the lower silt line is associated with a small flood deposit containing datable materials. The petroglyphs are typical of prehistoric artwork found elsewhere in the Colorado Plateau area and buried pottery shards found at this site are indicative of the Kayenta Branch of
FIGURE 9. Silt lines emplaced upon a panel of petroglyphs at Site Seven. The silt-lines postdate this artwork that was probably inscribed between 1000 A.D. and 1275 A.D.
the Anasazi culture (Personal Communication with Dee Hardy, Museum Curator, Anasazi Indian Village, Utah State Historical Monument, 1983). This culture was probably present in the southcentral Utah area from 1000 A.D. until approximately 1275 A.D. (Dee Hardy, Personal Communication, 1983). Organic debris within the small flood deposit associated with the lower silt line yields a date of $110 \pm 90$ yr BP (A-4006). This date represents a minimum age for the emplacement of the upper silt line. The maximum age of the upper silt line is constrained by the age of the petroglyphs, probably inscribed some 1000 to 700 yr BP. These age brackets are in accord with radiometric dates of $160 \pm 100$ (A-3628) and $180 \pm 50$ 14C yr BP for the correlated units at Sites Four (unit D) and Six. The $110 \pm 90$ 14C yr BP date represents a maximum age for the lower silt line (correlated to stratigraphic unit F at Site Four).

**DISCHARGE ESTIMATES**

Taking the positions of the silt lines as paleoflood maximum stage indicators, and the tops of the slackwater sedimentation units as representing minimum highwater surface stages (Baker and others, 1983), paleoflood water-surface profiles can be reconstructed from the various correlated stage indicators (Fig. 10). The profiles associated with units D-E and unit F of Site Four are the only profiles that can be directly reconstructed for a substantial length of the study reach from the sedimentologic evidence. However, assuming that the water-surface profiles of the other floods recorded at Site Four were at least subparallel to the better defined profiles, approximate
FIGURE 10. Positions and elevations of paleoflood highwater indicators. Some of the stage indicators can be correlated between sites on the basis of position and relative and absolute age constraints.
paleoflood profiles, and hence, discharges, also can be determined for the uncorrelated sedimentologic units.

The HEC-2 computer routine (Hydrologic Engineering Center, 1979) was used to determine the discharges associated with these paleoflood water-surface profiles. This program is a step-backwater routine based on the one-dimensional energy equation for gradually-varied flow,

\[ z_1 + y_1 + \frac{a_1 v_1^2}{2g} = z_2 + y_2 + \frac{a_2 v_2^2}{2g} + h_e \]  

(1)

(see Fig. 11 for defining illustration) (Chow, 1959, pg. 267). The standard-step computational method is employed with equation (1) to predict water-surface elevations for a series of surveyed cross sections (Feldman, 1981). The starting conditions (stage and discharge) are specified at the initial cross section (the downstream cross section for subcritical flow) and the routine computes an energy-balanced water surface for the subsequent cross section, taking into account estimated head losses associated with roughness and channel expansions or contractions within the incremental subreach between the sections. The computed water-surface elevation at the second cross section is then used as the initial condition for the next "step" upstream. This process continues until water-surface elevations are determined for each cross section of the study reach and a water-surface profile is defined (Feldman, 1981). For paleohydrological problems where the discharge, and perhaps the stage, are not known at the initial cross section, trials of various combinations of stage and discharge can be attempted until the HEC-2 generated profile matches the paleoflood
FIGURE 11. Definition diagram of conservation of energy for gradually varied flow for small channel slopes. $z$ is the elevation of the channel above an arbitrary datum, $y$ is the flow depth, $v$ is the mean flow velocity, $g$ is gravitational acceleration, $a$ is the velocity head coefficient accounting for non-uniform velocity distribution in a subdivided channel, and $h_e$ is the head loss between cross sections. Note that in natural stream systems, the water surface slope may deviate locally from both the channel slope and the energy slope depending on the local channel geometry. Modified from Richards, (1978).
\( \frac{\alpha_1 v_1^2}{2g} \)

\( y_1 \)

\( z_1 \)

\( \frac{\alpha_2 v_2^2}{2g} \)

\( y_2 \)

\( z_2 \)

ENERGY SLOPE

WATER SURFACE

CHANNEL BOTTOM
water surface stages defined by the highwater indicators. Numerous attempts with various combinations of discharges, stages, and roughness values for the data at Boulder Creek indicate that discharge is the primary profile controlling variable. Profiles initiated at different stages, but equal discharges, invariably converged beyond the first three to five cross sections.

The application of a gradually-varied flow model to determine discharges is more appropriate than using uniform flow formulae (such as the Manning Equation) in that natural river systems do not experience uniform flow. This is especially relevant in bedrock bounded systems where channel geometry cannot fully adjust to changing discharge conditions (Richards, 1978). HEC-2 also offers an improvement over the slope-area method (Dalrymple and Benson, 1967) of determining discharges, especially for reaches where there is some degree of channel complexity between sites of paleoflood highwater indicators. Through judicious placement of several cross sections, HEC-2 allows a more precise determination of energy losses through a complex reach than can be achieved by slope-area procedure, which restricts cross sections to sites of highwater indicators. An additional advantage in using the HEC-2 routine for Boulder Creek is the computational ability to separate the overbank flow conditions from those of the main channel. Thus, in the later discussion of the pool-and-riffle relationship to flow conditions, the hydraulics of the main channel flow can be divorced from the overbank flow conditions.

Twenty-seven cross sections were surveyed along the 600 m lower Boulder Creek study reach. The large number of cross sections
reflects the complex nature of the channel and the attempt to keep the channel increments between cross sections short enough to satisfy the assumption of gradually varied flow. The cross sections were generally surveyed to be perpendicular to the presumed direction of high-stage flow (not always equivalent to low-flow direction). However, some later adjustments to cross section orientations were necessary to meet this condition.

Modeling a 400 cubic meters per second (cms) subcritical flow results in a profile that best matches the paleoflood stage indicators left by the largest flood preserved in the sedimentologic record (stratigraphic units D-E and their assigned correlatives) (Fig. 12). Discharges of 350 and 450 cms result in profiles that diverge significantly (in the upstream direction) from the preserved highwater indicators, suggesting that this method of discharge estimation can be fairly precise. Discharges also were determined for each of the other seven sedimentologic units at Site Four, either by matching computed profiles with correlative paleoflood highwater indicators (for the case of unit F) or by assuming that the paleoflood water-surface profiles defined by only a single elevation are parallel to the better controlled paleoflood profiles. Resulting discharges for the four to eight flood events preserved in the geologic record are summarized in Table 2.

LARGE-FLOW FREQUENCY

The age constraints and discharge estimates outlined in the previous discussions indicate that at least four large flow events have occurred in the last 500 to 1000 years. At least one, and perhaps two (sedimentologic units D and E at Site Four) of the flows had dis-
FIGURE 12. HEC-2 generated profiles for discharges of 350, 400, and 450 cms. The 400 cms discharge appears to best match the highest paleoflood highwater indicators (Units D-E and cor-relatives) fairly well—especially considering that the slack-water sediments represent minimum paleoflood stages. The 350 and 450 cms computed profiles diverge significantly below and above, respectively, from the paleoflood water-surface profile defined by the geologic evidence. Critical depth was assumed for the 450 cms flow at the initial (downstream) cross section.
### Table 2. Paleoflood Discharges for the Flows Represented by Deposits at Site Four

<table>
<thead>
<tr>
<th>Stratigraphic Unit</th>
<th>Discharge AS Modeled By HEC-2 (CMS)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>200</td>
</tr>
<tr>
<td>B†</td>
<td>250</td>
</tr>
<tr>
<td>C</td>
<td>300</td>
</tr>
<tr>
<td>D</td>
<td>400</td>
</tr>
<tr>
<td>E†</td>
<td>400</td>
</tr>
<tr>
<td>F</td>
<td>275</td>
</tr>
<tr>
<td>G†</td>
<td>225</td>
</tr>
<tr>
<td>H†</td>
<td>150</td>
</tr>
</tbody>
</table>

*For the stratigraphic units where there are well-defined profiles (D-E,F), accuracy of the modeled discharges is probably on the order of ± 10-20%. For the slackwater sedimentation units without correlative deposits, the computed discharges are necessarily minimum estimates as there was an unknown depth of water above them.

†Has not been unequivocally determined to have been deposited from an independent flow event.
charges of about 400 cms. The radiometric dates (160 ± 100 and 180 ± 50 14C yr BP at Sites Four and Six) suggest that the 400 cms flow(s) occurred within the last 250 radiocarbon years. The length of the record represented by the slackwater deposits (At least 540 ± 100 14C yr BP at Site Six) implies that a 400 cms discharge probably represents the largest flow of approximately the past 500 radiocarbon years. The absence of additional, higher, silt lines overlying the petroglyphs may arguably indicate that there have been no larger flows within the last 700-1000 years.

The flood chronology presented here should not be taken as complete. Many of the depositional units that could not be positively distinguished as discreet floods in this study may indeed represent separate flow events. In addition, there is the possibility that flood sediments, especially those associated with lower magnitude events, have been deposited and subsequently removed during the evolution of the slackwater deposits. However, the paleoflood chronology preserved at Boulder Creek does give at least an approximation of the magnitudes and frequencies of extreme events that have affected this fluvial system over the last several centuries.

RIFFLE RELATIONSHIP TO LARGE-FLOW HYDRAULICS

With a knowledge of the magnitudes and approximate frequencies of large flow events experienced by Boulder Creek, an attempt can be made to relate reasonable large flood flow hydraulics to the Boulder Creek pool and riffle pattern. The riffles, excluding the rarer bedrock riffles, can be best considered as in-channel boulder deposits. The description of flow provided by the step-backwater calculations allows
for an evaluation of the positions and magnitudes of the boulder deposits within the context of large-flow hydraulics and coarse particle transport. Two approaches are taken to this problem: (1) appraise downstream changes in unit stream power at a given discharge by comparing flow conditions along the series of twenty-seven cross sections comprising the study reach; and (2), compare how the water-surface profiles and relative stream power change over individual pool-riffle sequences with increasing discharge.

UNIT STREAM POWER

HEC-2 allows for the separation of channel hydraulics from the surrounding flow conditions of the overbank areas. This allows direct computation of mean channel velocity (as opposed to mean cross-sectional velocity). Mean channel velocity, in conjunction with the known channel geometry, estimates of roughness coefficients, and assumptions about local flow conditions, can lead to an evaluation of unit stream power within the channel. Unit stream power ($\omega$) is the stream's ability to do work (rate of energy expenditure) divided by the unit width surface that the stream is acting upon (Bagnold, 1966). This work includes overcoming flow resistance (fluid viscosity, bedform roughness, and particle roughness) and transporting sediment (suspended load and bedload) (Bagnold, 1980). The intrinsic dependence of bedload transport on stream power makes this variable a logical starting point in evaluating the relationship of boulder transport and deposition to large-flow hydraulics. Recently established empirical and semi-empirical bedload transport relationships (Bagnold, 1980; Costa, 1983;
Williams (1983) have been fairly successful in using stream power as a transport criterion. Bagnold (1966) defined unit stream power as:

\[
\omega = \frac{\gamma Q S_f}{\text{flow width}} = \tau v
\]  

(2)

where \( \gamma \) is the specific weight of the fluid, \( Q \) is the discharge (in this case, the component of total discharge conveyed by the main channel), \( S_f \) represents the friction slope, \( \tau \) is the total channel shear, and \( v \) is the mean channel velocity.

Algebraically manipulating the uniform flow formulae for channel shear stress,

\[ T = \gamma R S_f \]  

(3)

where \( R \) is the hydraulic radius, and velocity (from the Manning Formula),

\[ v = \frac{R^{2/3} S_f^{1/2}}{n} \]  

(4)

where \( n \) is the Manning coefficient of roughness; so that

\[ v = \frac{R^{1/6} (\gamma^{1/2} R^{1/2} S_f^{1/2})}{n \gamma^{1/2}} \]  

(5)

and substituting in Equation (3),

\[ v = \frac{R^{1/6} (\omega/\gamma)^{1/2}}{n \gamma^{1/2}} \]  

(6)

a resulting relationship can be obtained that represents unit stream power as:

\[ \omega = \frac{\gamma n^2 v^3}{R^{1/6}} \]  

(7)

While it is recognized that the application of uniform flow formulae to non-uniform flow conditions may not be strictly valid, the lack of more general, computationally feasible, treatments precludes
a more rigorous analysis. In any case, most gradually varied flow models assume the uniform flow formulae to be valid for predicting energy losses at a given section (Chow, 1969, pg. 217). Therefore, their use in this manner at Boulder Creek is in keeping with established methodology and presumably does not introduce substantial error.

BOULDER DEPOSITS AND DOWNSTREAM STREAM-POWER VARIATIONS

Unit channel stream power was computed from equation (7) for the 400 cms flow (associated with units D-E of Site Four) at each of the twenty-seven surveyed cross sections. Mean channel velocity was taken directly from the modeled hydraulics. The hydraulic radius was calculated by dividing the main channel flow area by the immobile surface bounding it. The boundary between the channel and overbank flow components was considered frictionless. A Manning's $n$ roughness value of 0.035 was used for each of the cross sections. The specific weight of the fluid was assumed to be 9800 N/m$^3$. The hydraulic parameters and resulting stream power magnitudes are tabulated in Appendix A.

The results of this exercise suggest there is a relationship between downstream variations in 400 cms stream power and riffle positions (Fig. 13). All ten of the riffles within the study reach are, without exception, located at cross sections that experience local stream power minima, or are within reaches of decreasing stream power. This relationship seems reasonable in that the coarse bedload particles would be expected to drop out of the flow once the stream power available for transport drops below a critical stream power threshold required of the boulders to maintain motion.
FIGURE 13. Calculated unit channel stream power for a 400 cms discharge. Stream power varies from section to section depending on the hydraulic characteristics at each cross section. The boulder comprised riffles are all located at reaches of decreasing stream power or at cross sections that experience local stream power minima.
An indication that the stream power associated with a 400 cms flow may indeed be important in Boulder Creek's pool and riffle pattern development is a comparison between the apparent threshold stream power magnitudes observed here and established sediment transport relationships. Williams (1983) compiled data offered by several authors regarding coarse particle sediment transport observations and proposed empirically derived limiting relationships on the movement, and non-movement, of large bedload particles (Fig. 14a). The plotted positions of the points representing the average intermediate diameter of the five largest boulders at each of the ten Boulder Creek riffles (Table 3) are either directly on, or above, the lower limiting transport capability for stream powers associated with a 400 cms flow (Fig. 14b). The implication is that a 400 cms flow is the minimum discharge required to have transported many of the riffle comprising boulders to their present positions. For the riffles where the boulder sizes plot directly on the lower limiting line (Fig. 14b), discharges of any lesser magnitude would have associated stream powers less than those of recognized transporting capability.

The positions of the riffle boulder averages that do plot further within the range of competent conditions may reflect several factors. These boulder accumulations are possibly the result of lower magnitude events and are consequently an overprint superimposed upon the riffle positions controlled by larger flows. There are also potential errors in flow modeling, especially in that the assumption
FIGURE 14. Modified from Williams' (1983) compilation of field measured stream power as a function of transported boulder size.

A. Williams (1983) fitted, by eye, an approximate limiting line that represents "the lowest unit stream power, which, according to presently available measurements can move that size particle". B. The same relationship as A with the addition of the Boulder Creek riffle boulder measurements and their associated 400 cms unit stream powers (Table 3). The positions of these points are all on or above the lower limiting line proposed by Williams (1983). A smaller discharge and its associated smaller stream power magnitudes would be insufficient to transport many of the riffle comprising boulders.
OBSERVED TRANSPORT

UNIT STREAM POWER (N/m²/s)

10,000
1,000
100
10

INTERMEDIATE DIAMETER OF PARTICLE (mm)

10
100
1,000
10,000

APPROXIMATE LIMITING LINE

BOULDER CREEK BOULDERS FOR 400 cms FLOW

APPROXIMATE LIMITING LINE
### TABLE 3. RIFFLE BOULDER MEASUREMENT DATA

<table>
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<tr>
<th>RIFFLE</th>
<th>NUMBER OF BOULDERS MEASURED</th>
<th>AVERAGE DIAMETER OF THE FIVE LARGEST BOULDERS (mm)</th>
<th>UNIT STREAM POWER* (N/M/S)</th>
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</tr>
<tr>
<td>10</td>
<td>10</td>
<td>950</td>
<td>640</td>
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* Stream power magnitudes are those associated with a 400 cms discharge (Fig. 13).
of gradually varied flow is probably not always be appropriate in a fairly tortuous canyon. Another factor of probable importance is that stream power is not only expended in transporting sediment. Total channel shear is the sum of the boundary friction forces (directly related to sediment transport) and drag forces related to channel geometry irregularities (such as bends, sand dunes, and the the riffles themselves) (Einstein, 1950). At cross sections where a greater fraction of the stream power is needed in overcoming the latter, a smaller amount of energy will be available for sediment transport. Consequently, for a given stream power, boulders at these sites may experience smaller magnitude tractive forces than boulders at cross sections of more efficient transporting regime, resulting in the deposition of boulders smaller than predicted. Only a more complete understanding of channel hydraulics and stream power expenditure can eliminate the difficulties in resolving the precise proportion of the stream power participating in coarse particle transport from the stream's total energy expenditure.

POOL AND RIFFLE STREAM POWER VARIATION WITH DISCHARGE

It is also illustrative to examine how the modeled flow hydraulics over the pools and riffles varies with discharge; especially in that this approach has been the tactic often applied in studying alluvial pool and riffle hydraulics. Keller (1971) noted that for Dry Creek, California, measured bottom velocity (his index to sediment transport) over the pools increased faster than over the riffles with increasing discharge. The bottom velocity in the pools eventually surpassed the velocity in the riffles (a "reversal") at about the 1.2 year recurrence interval flow (Keller, 1971). Lisle (1979) measured mean shear
stress over a riffle-pool sequence in the East Fork River of Wyoming and also demonstrated a reversal occurring at about bankfull stage. Using a step-backwater routine similar to HEC-2, Richards (1978) modeled flows of various stages over a pool and riffle sequence in South Ontario, Canada. He found that with increasing discharge, water-surface slope over the riffles decreased while slopes over the pools increased, but never to the point where the riffles were "drowned out" (Richards, 1978). Richards (1978) also noted that mean velocity, as predicted by the model, did increase proportionately faster in the pools than it did in the riffles with rising stage, but not to the point of a reversal for the range of his modeled discharges.

The results of modeling Boulder Creek flows at discharges ranging from 2.5 cms (approximate low-flow discharge) to bankfull (approximately 50 cms) generally support the above observations. However, modeling flows of much greater than bankfull adds additional information into the hydraulics of this type of pool and riffle pattern. Figure 15 illustrates that, as Richards (1978) points out, water-surface slope does attenuate over the pool and riffle pattern for flows up to near bankfull discharge. However, at flows greater than this (up to 400 cms), the water-surface slope over the riffles becomes less than that over the pools. The end result is that, in general, the low-flow pools become the reaches of greatest water surface slope (and energy slope), and the riffles become reaches of lower water-surface slopes during the large magnitude, low frequency events. As would be expected, there is a corresponding reversal in calculated stream power over many of the pool-riffle sequences (Fig. 16).
FIGURE 15. HEC-2 computed profiles for discharges ranging between 10 and 400 cms in addition to the surveyed low-flow profile (accurately modeled as 2.5 cms). Note that the relative water surface slopes over the low-flow pool and riffles become reversed with increasing stage. The modeled profiles for the downstream 100 m of the study reach should be considered approximate in that an assumed initial stage was used for the first cross section. Three to four "steps" are generally required until a profile independent of the assumed stage is obtained. A 50 cms discharge represents approximate bank-full conditions.
FIGURE 16. Calculated unit stream power as a function of discharge over four representative pool-riffle sequences. For low flows, unit stream-power is invariably greater at the riffles, but at high flows, stream power becomes greater over the low-flow pools.
As noted above, the boulder deposits comprising the Boulder Creek riffles are found along reaches of low or decreasing stream power for high-magnitude flows. Moreover, these are reaches that experience relatively lower water-surface slopes during these events. These intrinsically related observations are apparently imposed onto this system by the morphology of the Boulder Creek canyon. Up to approximately bankfull stage, the water-surface profile seems to be primarily influenced by a relatively static channel-bottom pool-and-riffle topography and the confining banks, but for stages greater than bankfull, the Boulder Creek canyon configuration apparently becomes increasingly important in controlling water-surface slope. A comparison of the 400 cms flow profile with a plan-view map of the study reach (Figs. 3 and 17) suggests that the large-flow water-surface slope variations are associated with certain types of canyon geometry. The reaches of low water-surface slope during a 400 cms discharge occur immediately upstream of canyon bends and constrictions where hydraulic damming impedes flow conveyance, and at locales of canyon widening because of reduced flow velocities and hence, stream power, associated with flow expansion.

A scenario can be visualized where at high discharges, riffle boulders are mobilized when available stream power surpasses the transport threshold. These boulders are transported through the low-flow pools (reaches of greater stream power during competent flows) and deposited where canyon morphologies are such that available stream power is not sufficient to maintain transport (i.e. upstream of bends and con-
FIGURE 17. 400 cms flow profile and unit stream power variations in relation to the Boulder Creek canyon morphology. Local stream-power and water-surface slope minima occur immediately upstream of canyon bends and constrictions, and at canyon expansions.
strictions, and downstream of expansions). Deposition may be at the next downstream riffle position, or further, depending on the flow magnitude, the sizes of the boulders being transported, and the downstream stream-power variations. An important aspect of this model is that it does not depend on temporally varying conditions controlling the boulder deposition, but only on spatial changes in available stream power in the downstream direction.

This hypothesis of canyon geometry control of the Boulder Creek's pool and riffle pattern development was further tested by mapping the riffle positions for an additional 5.9 km upstream (Fig. 18). Each of the 85 mapped riffles was assigned a relative value of one through five based on riffle size (factors included a subjective evaluation of the number and size of the riffle comprising boulders, length of the riffle, and magnitude of water-surface elevation drop over the riffle). A magnitude one riffle is one that was barely discernible, and magnitude five representing the largest and most turbulent riffles. Of the 85 riffles, 65 are located immediately upstream of canyon bends or constrictions or downstream of valley expansions (Fig. 19); corresponding to sites of lower stream powers in the modeled reach (Table 4). Four of the riffles are associated with mass wasting of bouldery terrace deposits, leaving only sixteen out of the 85 mapped riffles that have no readily apparent relationship to canyon morphology (and they may be related to changes in channel gradient, a factor not important in the modeled reach, but possibly of greater importance in the mapped reach.). Of the 38 largest riffles (magnitudes four and five), 34 are associated with channel bends, constrictions, or expansions.
FIGURE 18. Positions, magnitudes, and canyon configurations for all
the alluvial riffles between the confluence of Deer and Boulder
Creeks and the Boulder Creek confluence with the Escalante
River. A vast majority of the riffles are located at sites
that have channel and canyon geometries associated with relatively
low large-flow stream power magnitudes. The reach not mapped
was avoided because of hazardous conditions.
FIGURE 19. Magnitude 5 riffles. A. Immediately upstream of a canyon constriction. During large floods, flow is hydraulically dammed behind the constriction and the riffle comprising boulders are deposited in this reach of relatively lower large-flow stream power. B. Immediately downstream of a canyon expansion where reduced large-flow velocities result in lower stream-power magnitudes.
## Table 4. Relationship of Boulder Creek Riffle Positions to Canyon Morphology

<table>
<thead>
<tr>
<th>Assigned Magnitude</th>
<th>Immediately Upstream of Canyon Bends</th>
<th>Immediately Upstream of Canyon Constrictions</th>
<th>Immediately Downstream of Canyon Expansions</th>
<th>Mass Wasting From Bouderly Terraces</th>
<th>No Apparent Morphologic Control</th>
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Of the twenty-eight abrupt bends in the mapped reach, all but one have riffles immediately upstream. Considering these observations, it seems evident that a majority of the pool and riffle positions within the Boulder Creek stream system are readily explained by the hydraulics of large and infrequent floods in an irregular canyon.

CONCLUSION

Hydraulic modeling of large paleofloods at Boulder Creek, Utah indicates that the boulder comprised riffles of this stream system occur in reaches of relatively low, or decreasing, stream power for larger flow magnitudes (Fig 13). The boulder deposits occur where descending stream power approaches the critical transporting power required of the stream to maintain the motion of the boulders in transport (Fig. 14b). The downstream stream power variations are apparently influenced by canyon morphology. The regions of lowest stream power occur where there is hydraulic damming behind canyon bends and constrictions and where flow velocity decreases at canyon expansions (Fig. 17). This model of pool and riffle pattern development accords well with Keller's (1971) and Lisle's (1979) observations of relatively lower values of stream power (or indices thereof) occurring over the riffles during high discharges in alluvial stream systems (Fig. 16).

The sedimentologic evidence suggests that the flows that affect this aspect of channel morphology at Boulder Creek have recurrence intervals on the order of several hundreds of years and are about an order magnitude greater than bankfull. This observation agrees with the notion that rare flood events may be important channel shapers in some fluvial environments (Baker, 1977) and more specifically
with Graf's (1979) assertion that "...any theory attempting to explain the distribution and dynamics of rapids in canyon rivers must...account for the effects of climatic/hydrologic conditions that have recurrence intervals greater than 100 years".

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Contents of this publication do not necessarily reflect the views and policies of the United States Department of the Interior, nor does mention of trade names or commercial products constitute their endorsement by the United States Government.
REFERENCES


**APPENDIX A**

*CHANNEL HYDRAULICS FOR A 400 CMS DISCHARGE*

<table>
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<tr>
<th>SECTION</th>
<th>MANNING'S n</th>
<th>V (M/S)*</th>
<th>R (M)</th>
<th>γ (N/M³)</th>
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* Obtained directly from step-backwater computed hydraulics