PALEOHYDROLOGY OF POOL AND RIFFLE PATTERN DEVELOPMENT:
BOULDER CREEK, UTAH

by

Jim E. O'Connor

A Prepublication Manuscript Submitted
To The Faculty Of The

DEPARTMENT OF GEOSCIENCES

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

1985

STATEMENT BY AUTHOR

This manuscript, prepared for publication in the Geological Society of America Bulletin, has been submitted in partial fulfillment of requirements for an advanced degree at the University of Arizona and is deposited in the Anteves Reading Room to be made avialable to borrowers as are copies of regular theses and dissertations.

Brief quotations from this manuscript are allowable without special permission, provided that accurate acknowledgement of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the department, or the graduate student coordinator, when in their judgement the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGHNED: Jim E. O'Connor

APPROVAL BY RESEARCH ADVISORY COMMITTEE

This manuscript has been approved for submission on the date shown below:

Victor R. Baker — 21 January 1985

W B Bull — 22 January 85

Graduate Student Coordinator, or Head of Department — Date: 2-21-85

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 ± 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.

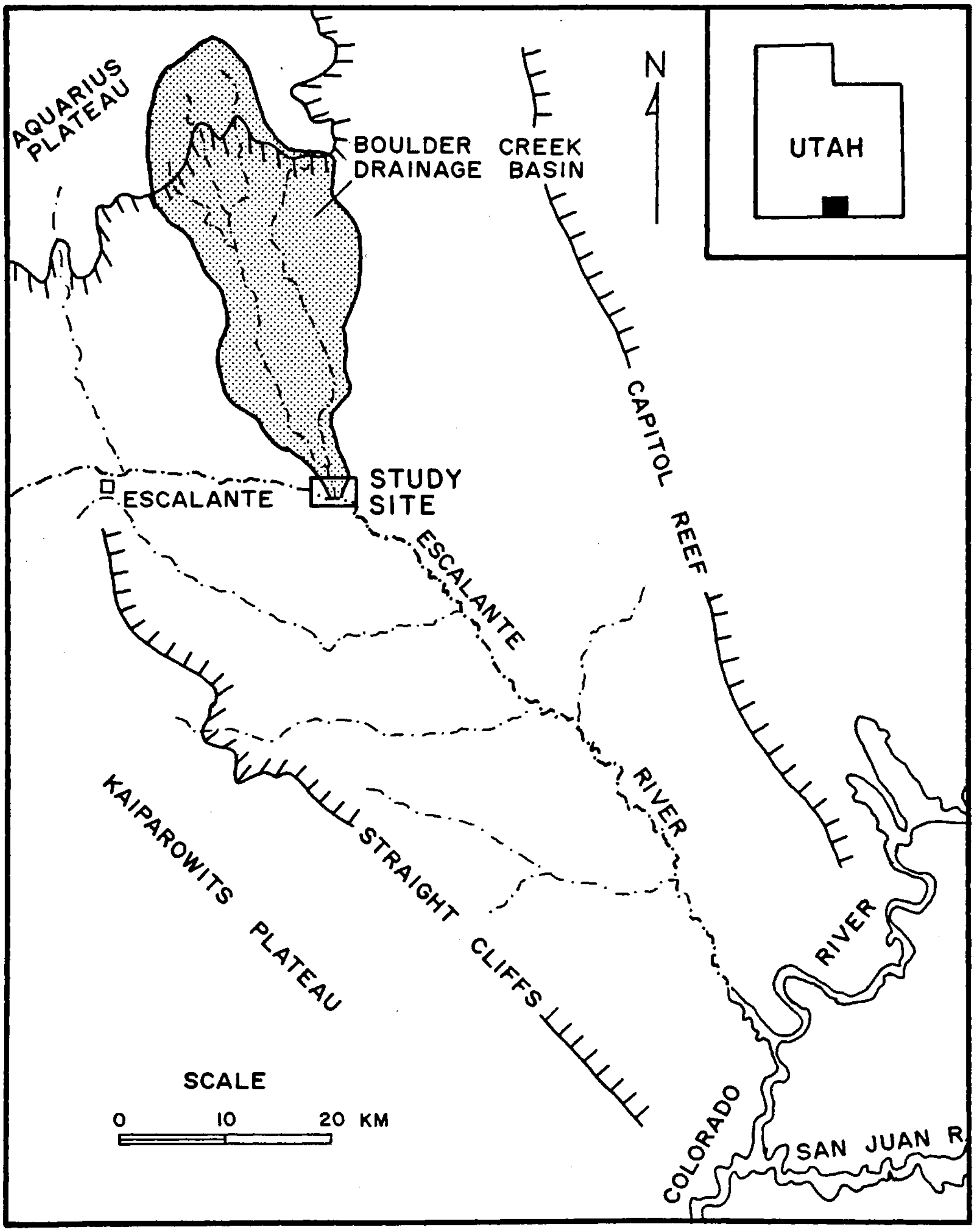
Wolman and Miller (1960) proposed that the one to two year recurrence interval flow event is a primary agent of geomorphic work in fluvial systems. This concept has been ammended by recent workers who have noted the potential for catastrophic response associated with large-magnitude, low-frequency, flooding. In certain physiographic environments, such as the American southwest, rare hydrologic events may be the dominant force in controlling various aspects of channel momrphology (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 km^2 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.


AQUARIUS PLATEAU
BOULDER CREEK
DRAINAGE BASIN
N
UTAH
STUDY SITE
ESCALANTE
ESCALANTE
RIVER
CAPITOL REEF
KAIPAROWITS PLATEAU
STRAIGHT CLIFFS
RIVER
COLORADO
SAN JUAN R
SCALE
0
10
20 KM

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 Creeks'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.

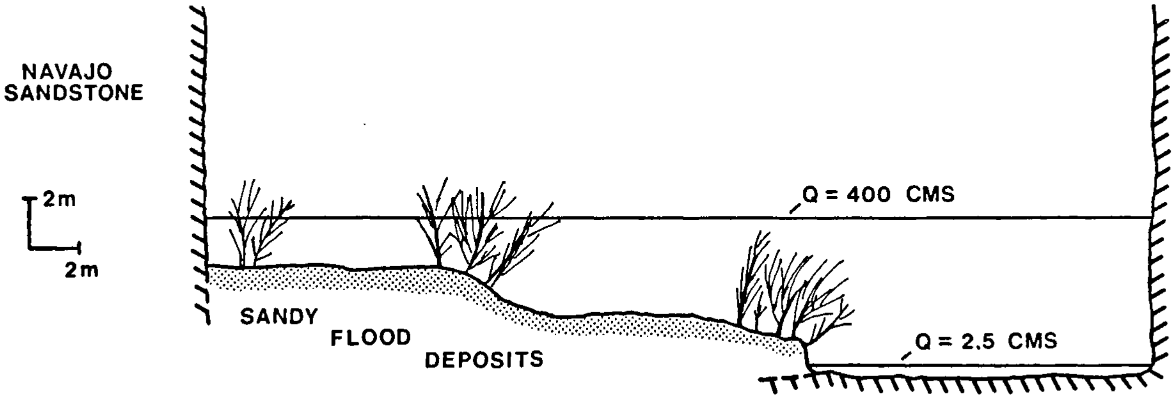

NAVAJO SANDSTONE
2m
2m
Q = 400 CMS
SANDY
FLOOD
DEPOSITS
Q = 2.5 CMS

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.

6

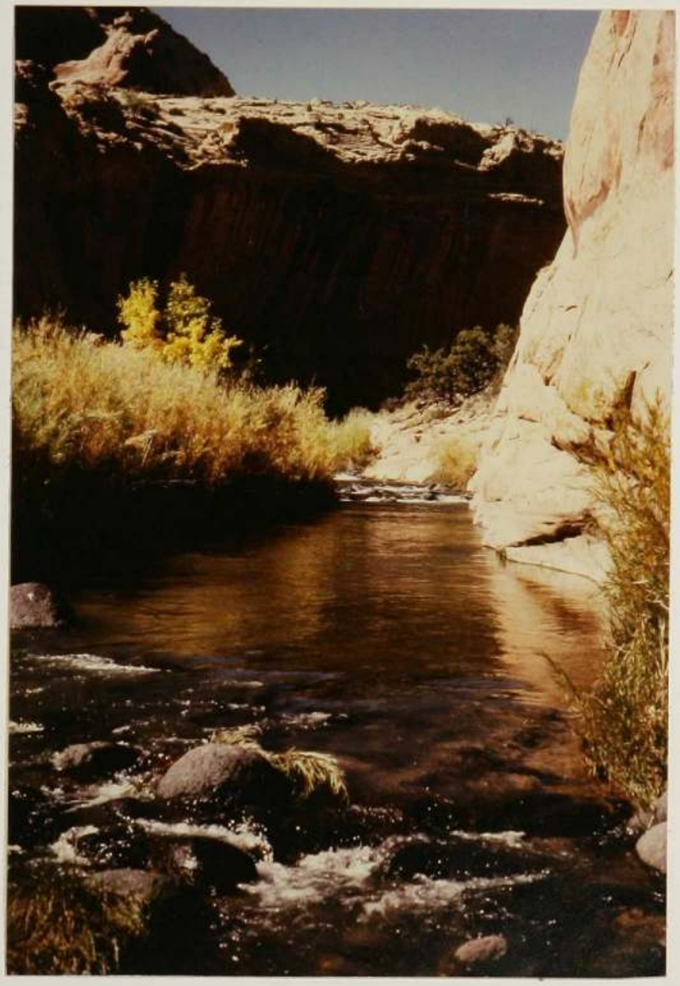
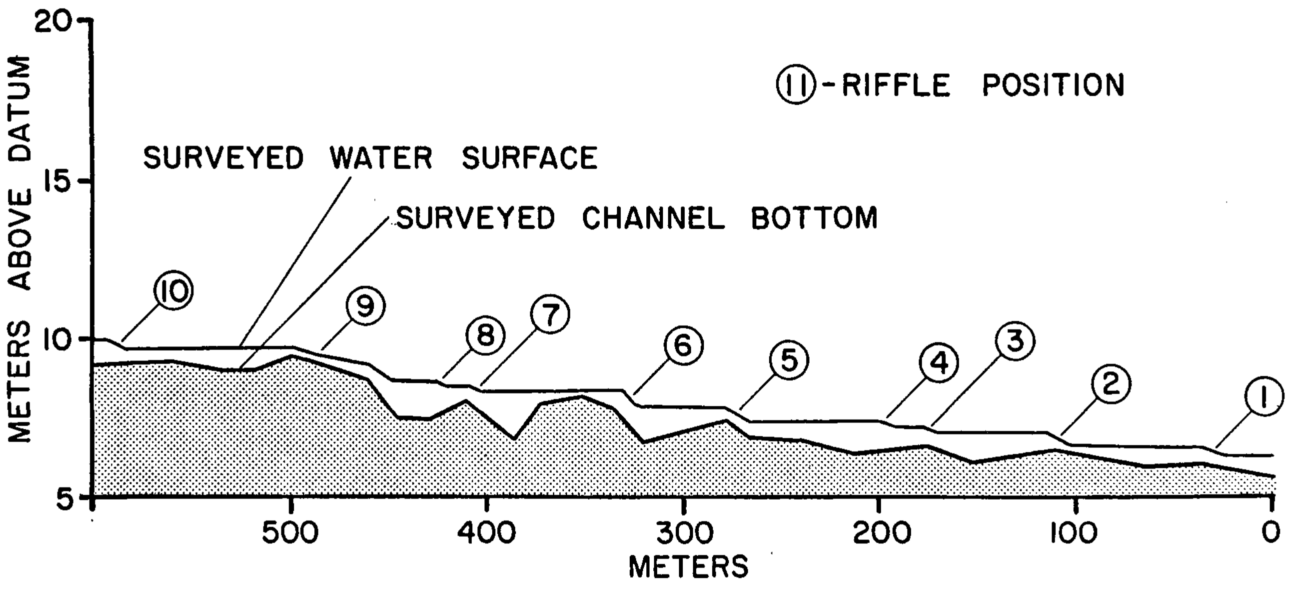


FIGURE 4. Surveyed profile of low-flow water surface and channel bottom for the 0.6 km study reach upstream of the Escalante confluence. The low-flow water surface drops in a step-wise manner over the channel riffles. All the riffles are formed by basaltic boulder accumulations except for a bedrock riffle (not mapped) immediately downstream from boulder riffle 9.


20
15
10
5
METERS ABOVE DATUM
⑪-RIFFLE POSITION
SURVEYED WATER SURFACE
SURVEYED CHANNEL BOTTOM
⑩
⑨
⑧
⑦
⑥
⑤
④
③
②
①
500
400
300
200
100
0
METERS

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.

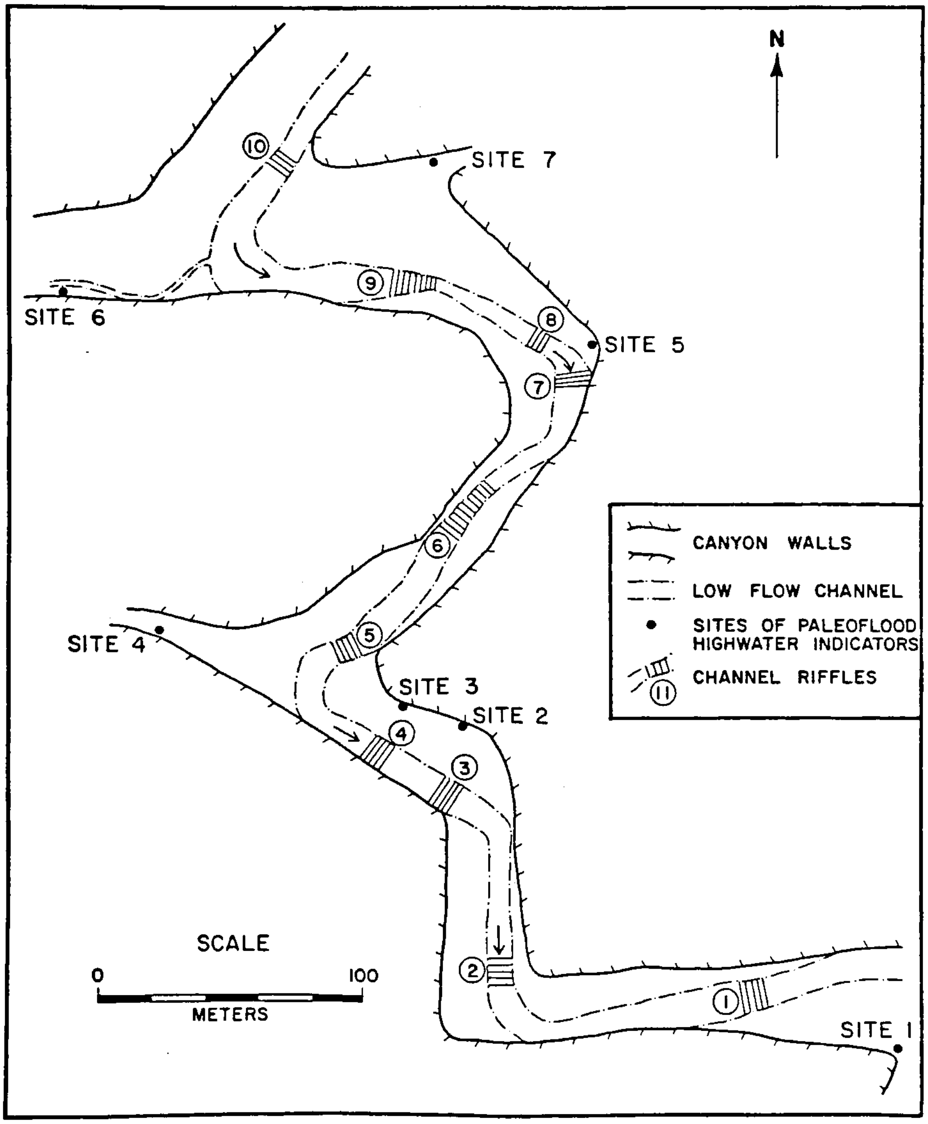
BOULDER CREEK FLOOD CHRONOLOGY

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.


N
SITE 7
SITE 6
SITE 5
SITE 4
SITE 3
SITE 2
SITE 1
10
9
8
7
6
5
4
3
2
1
CANYON WALLS
LOW FLOW CHANNEL
SITES OF PALEOFLOOD HIGHWATER INDICATORS
CHANNEL RIFFLES
11
SCALE
0
100
METERS

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).

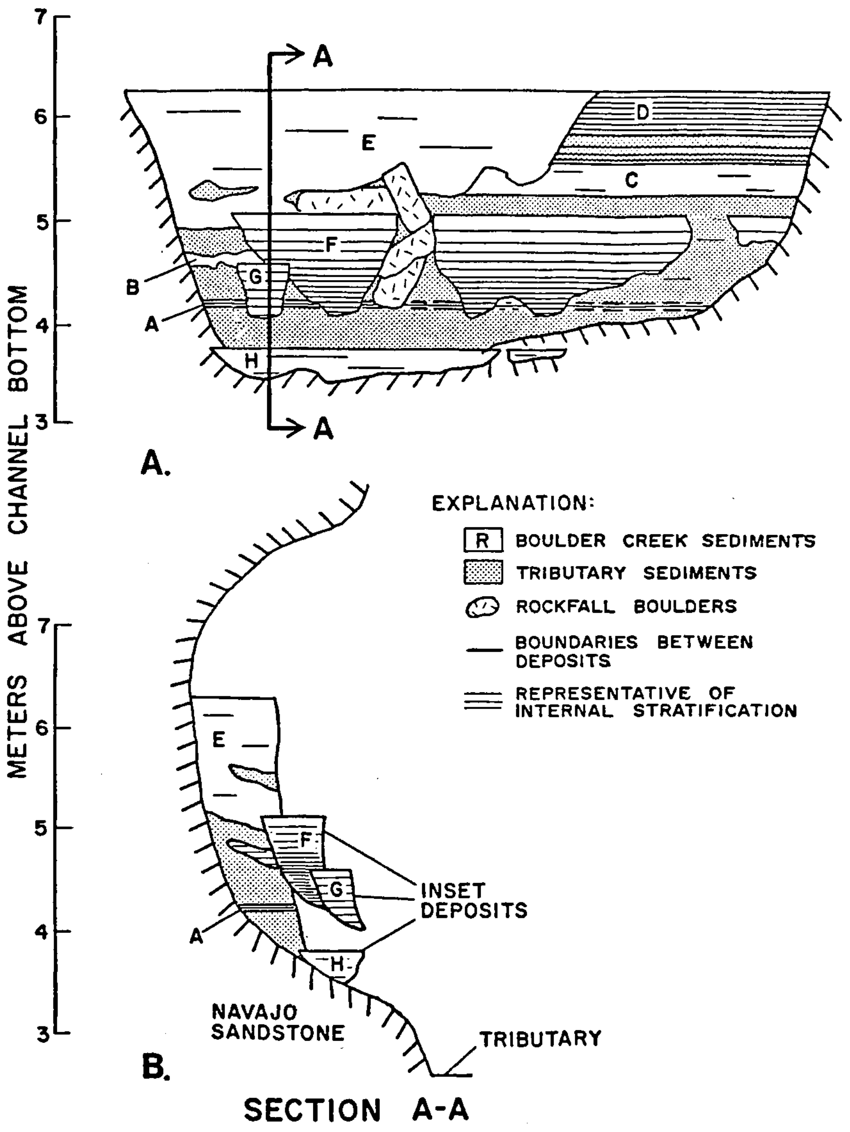
Within the study reach at Boulder Creek, there are two multiple unit slackwater deposits (Sites Four and Six of Fig. 5). In addition to the slackwater sediments, there are vestiges of silt lines preserved along protected portions of some of the canyon walls (Sites One, Two, Three, Five, and Seven of 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.


METERS ABOVE CHANNEL BOTTOM
7
6
5
4
3
A
A
B
A
C
D
E
F
G
H
A.
EXPLANATION:
R BOULDER CREEK SEDIMENTS
TRIBUTARY SEDIMENTS
ROCKFALL BOULDERS
BOUNDARIES BETWEEN DEPOSITS
REPRESENTATIVE OF INTERNAL STRATIFICATION
7
6
5
4
3
E
F
G
H
A
INSET DEPOSITS
NAVAJO SANDSTONE
TRIBUTARY
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}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*

STRATIGRAPHIC UNIT	ELEVATION ABOVE DATUM (m)†	DESCRIPTION	AGE CONSTRAINTS	COMMENTS
	11.09	Planar laminated sandy silt. Brown (7.5YR 5/4) Laminations 2-3mm thick and generally fine upwards. Abundant fine-grained organics concentrated in fine lamina. Lower and upper boundaries abrupt and planar.	Stratigraphically oldest unit in the deposit	Interpreted to represent a discreet flow event. Based on sedimentologic nature and position, may be correlative with the lower, older unit at Site Six
	11.63	Fine silt to silty-fine sand. Brown (7.5YR 5/4). Undulating laminations thicken (0-2cm) and coarsen upwards. Lower and upper boundaries abrupt and planar.	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, G, and H. If Unit B is not inset into the the tributary sediments, but was accreted vertically, it is probably older than Units C and D, and definitely older than Units E,F,G, and H.	Chronological position not known with certainty. If inset, could be associated with other events represented by deposits here. Therefore, cannot be delineated unequivocably as a discreet flow event.
	12.38	Massive, brown (7.5YR 5/4 silty fine to silty-medium sand. Top boundary abrupt and straight. Lower boundary clear and straight.	By stratigraphic position, older than Units D,E,F,G, and H. Younger than Unit A and possibly Unit B.	Bounded above and below by tributary sediments. Therefore, regarded as representing a single flow event
	13.09	Finely laminated sandy silt to silty medium sand. Brown (7.5YR 5/4). Laminations thicken (0-5cm) and coarsen upwards. Some crossbedding features in the top 10cm. Top of deposit capped by a 2mm layer of fine silt. 3cm thick horizon of transported organic debris at 25 cm from the top of the unit. Lower boundary abrupt and planar.	Fine organics within this deposit were radiometrically dated at 160± 100 ^{14}C yr BP (A-3628).	Bounded 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.
	13.09	Massive pink (7.5YR 5/4) silty-fine to silty-medium sand. Some wavy lamina of finer-grained (coarse silt to fine sand) sediments within the lower 10cm paralleling the wavy, abrupt lower boundary.	Inset in Units D and and C. Therefore constrained to be of equal age or youger with respect to Unit D. Younger than Unit C.	Cannot be destinguished as a separate flow event than that represented by Unit D.
	11.95	Brown (7.5YR 4/6) 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.	Inset into Units A,B, and E. Therefore, of equal age or younger with respect to those deposits. Diseminated organics from a correlative deposit at Site Seven yields an age of 110±90^{14}C yr BP (A-4006).	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.
	11.50	Section collapsed before described.	Inset into Units F, B, and A. Therefore of equal age or younger with respect to Unit F.	Lack of age constraints precludes delineating Unit G as a separate flow event than that depsiting Unit F.
	10.69	Massive brown (7.5YR 4/6) silty-fine to medium sand. Abundant large organic debris in the top 5cm. Top boundary planar. Deposit lies on bedrock at the base of the alcove.	Lowest inset deposit, therefore the stratigraphically youngest unit at Site Four.	Lack of age constraints precludes delineating Unit H as a separate flow event than that depositing Unit G (and F).

*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 cobbly 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.


R.C.
R.C.

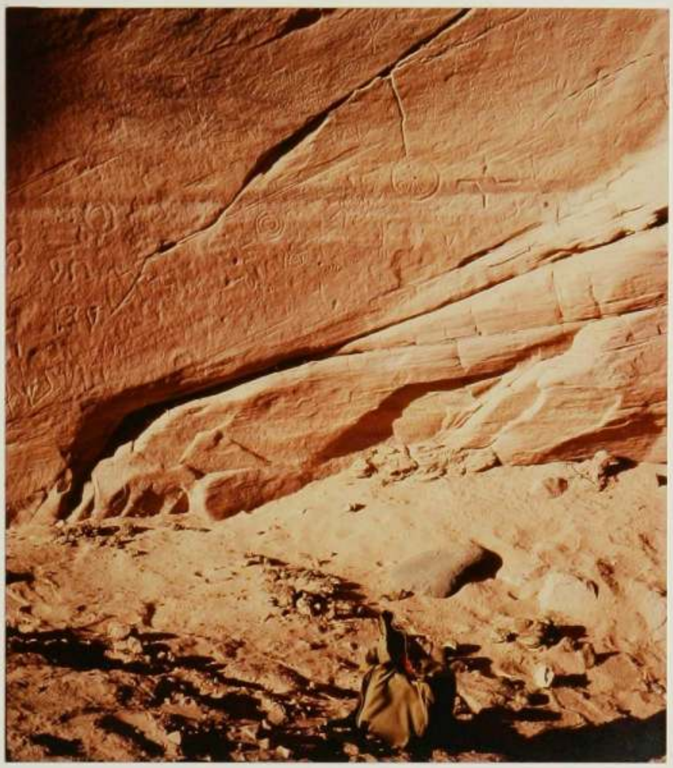
sents at least a partial paleoflood record for approximately the last 500 years.

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.

17

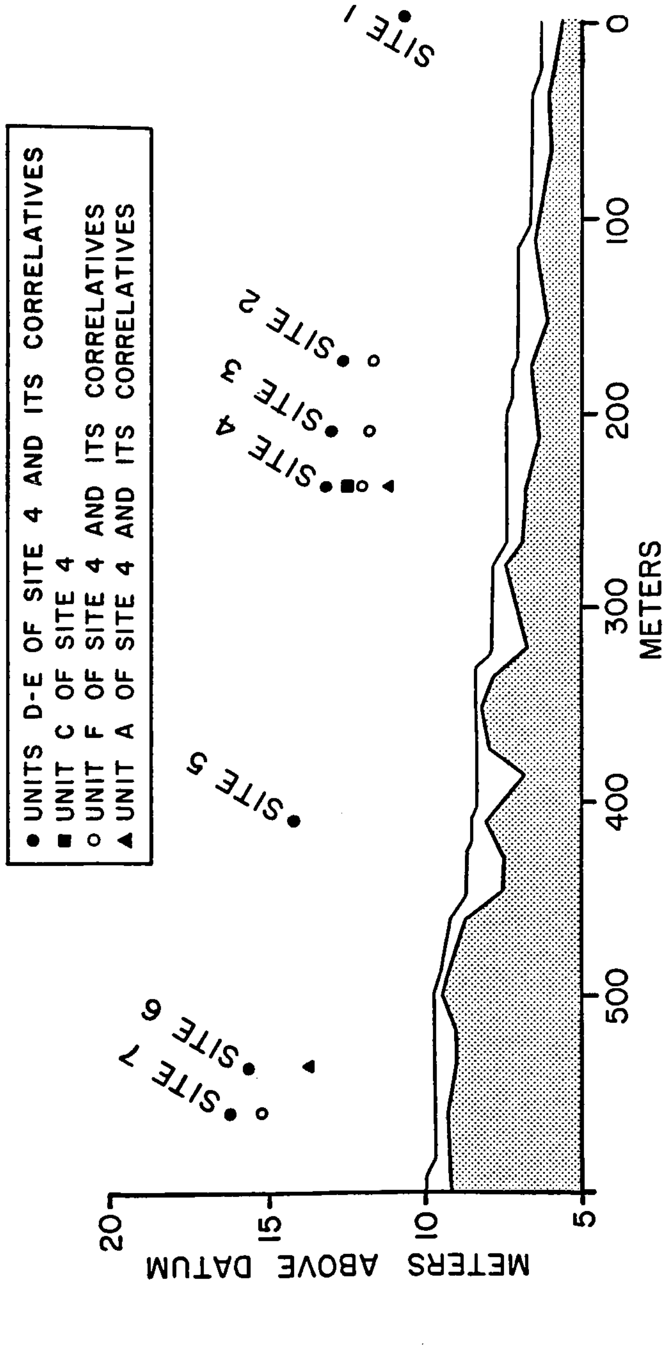


the Anasazi culture (Personal Communication with Dee Hardy, Museum Curator, Anasazi Indian Village, Utah State Historical Monument, 1983). This culture was probably present in the southcentral Utah area from 1000 A.D. until approximately 1275 A.D. (Dee Hardy, Personal Communication, 1983). Organic debris within the small flood deposit associated with the lower silt line yields a date of 110 ± 90 ^{14}C 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 ± 100 (A-3628) and 180 ± 50 ^{14}C yr BP for the correlated units at Sites Four (unit D) and Six. The 110 ± 90 ^{14}C 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, assumming 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.


● UNITS D-E OF SITE 4 AND ITS CORRELATIVES
■ UNIT C OF SITE 4
○ UNIT F OF SITE 4 AND ITS CORRELATIVES
▲ UNIT A OF SITE 4 AND ITS CORRELATIVES
SITE 1
SITE 2
SITE 3
SITE 4
SITE 5
SITE 6
SITE 7
METERS ABOVE DATUM
20
15
10
5
METERS
0
100
200
300
400
500

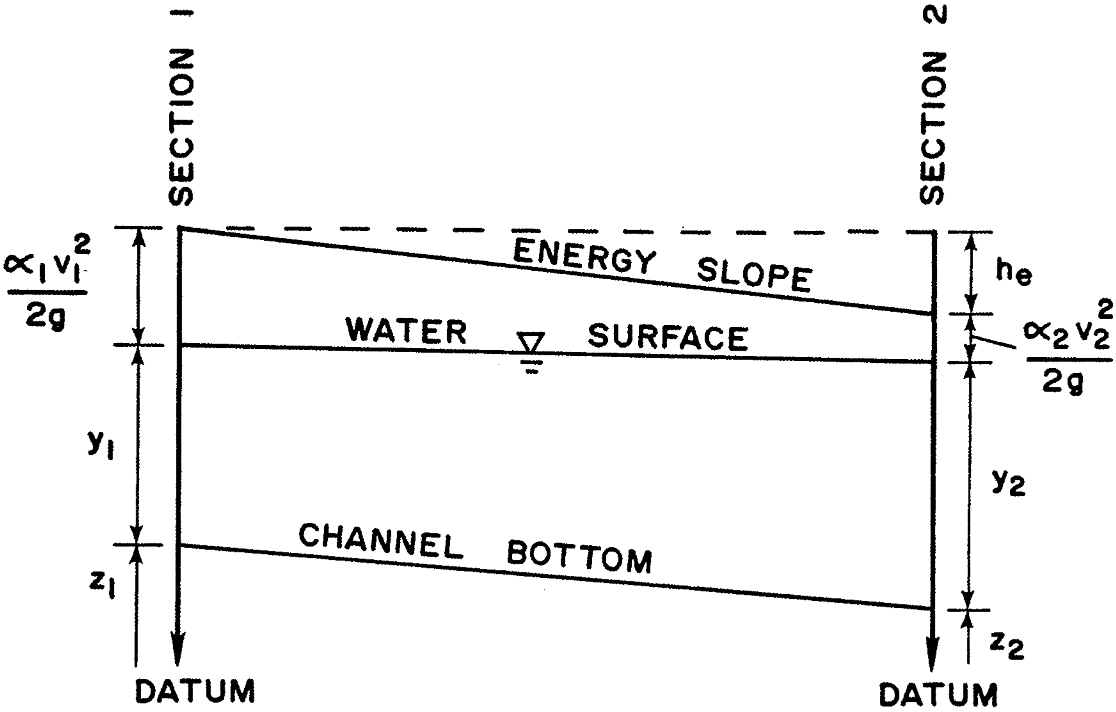
paleoflood profiles, and hence, discharges, also can be determined for the uncorrelated sedimentologic units.

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,

$$z_1 + y_1 + \frac{\alpha_1 v_1^2}{2g} = z_2 + y_2 + \frac{\alpha_2 v_2^2}{2g} + h_e \qquad (1)$$

(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, α 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).


SECTION 1
SECTION 2
$\frac{\alpha_1 v_1^2}{2g}$
ENERGY SLOPE
h_e
WATER SURFACE
$\frac{\alpha_2 v_2^2}{2g}$
y_1
y_2
CHANNEL BOTTOM
z_1
z_2
DATUM
DATUM

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.

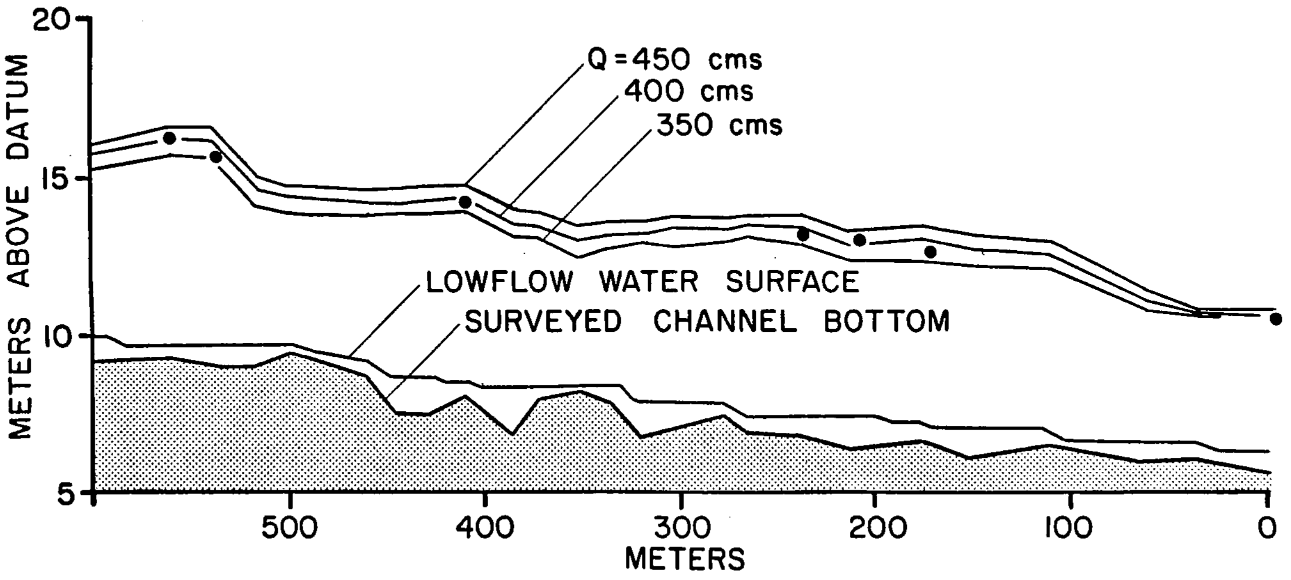
Twenty-seven cross sections were surveyed along the 600 m lower Boulder Creek study reach. The large number of cross sections reflects the complex nature of the channel and the attempt to keep the channel increments between cross sections short enough to satisfy the assumption of gradually varied flow. 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 correlatives) fairly well--especially considering that the slackwater 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.



Q = 450 cms
400 cms
350 cms
LOWFLOW WATER SURFACE
SURVEYED CHANNEL BOTTOM
METERS ABOVE DATUM
20
15
10
5
500
400
300
200
100
0
METERS

TABLE 2. PALEOFLOOD DISCHARGES FOR THE FLOWS REPRESENTED BY DEPOSITS AT SITE FOUR

STRATIGRAPHIC UNIT	DISCHARGE AS MODELED BY HEC-2 (CMS)*
A	200
B†	250
C	300
D	400
E†	400
F	275
G†	225
H†	150

*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 unequivocably determined to have been deposited from an independent flow event.

charges of about 400 cms. The radiometric dates (160 ± 100 and 180 ± 50 ^{14}C 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 ^{14}C 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 calcualtions 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 (ω) 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:

$$\omega = \frac{\gamma Q S_f}{\text{flow width}} = \tau v \qquad (2)$$

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

Algebraically manipulating the uniform flow formulae for channel shear stress,

$$\tau = \gamma R \, S_f \qquad (3)$$

where $\underline{R}$ is the hydraulic radius, and velocity (from the Manning Formula),

$$v = \frac{R^{2/3} \, S^{1/2}}{n} \qquad (4)$$

where $\underline{n}$ is the Manning coefficient of roughness; so that

$$v = \frac{R^{1/6} (\gamma^{1/2} R^{1/2} S_f{}^{1/2})}{n \gamma^{1/2}} \qquad (5)$$

and substituting in Equation (3),

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

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

$$\omega = \frac{\gamma n^2 v^3}{R^{1/6}} \qquad (7)$$

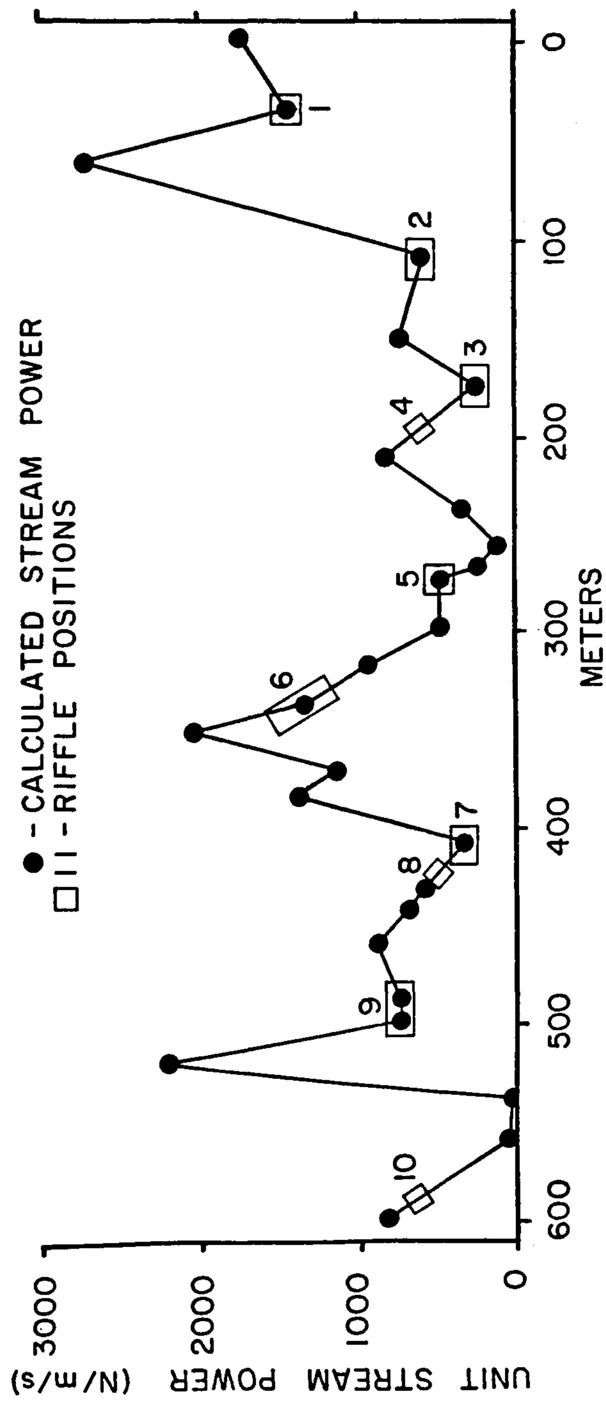
While it is recognized that the application of uniform flow formulae to non-uniform flow conditions may not be strictly valid, the lack of more general, computationally feasible, treatments precludes a more rigorous analysis. In any case, most gradually varied flow models assume the uniform flow formulae 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 $\underline{n}$ 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.


● - CALCULATED STREAM POWER
□ I I - RIFFLE POSITIONS
UNIT STREAM POWER (N/m/s)
3000
2000
1000
0
0
100
200
300
400
500
600
METERS
1
2
3
4
5
6
7
8
9
10

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 <u>minimum</u> 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 funtion 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.

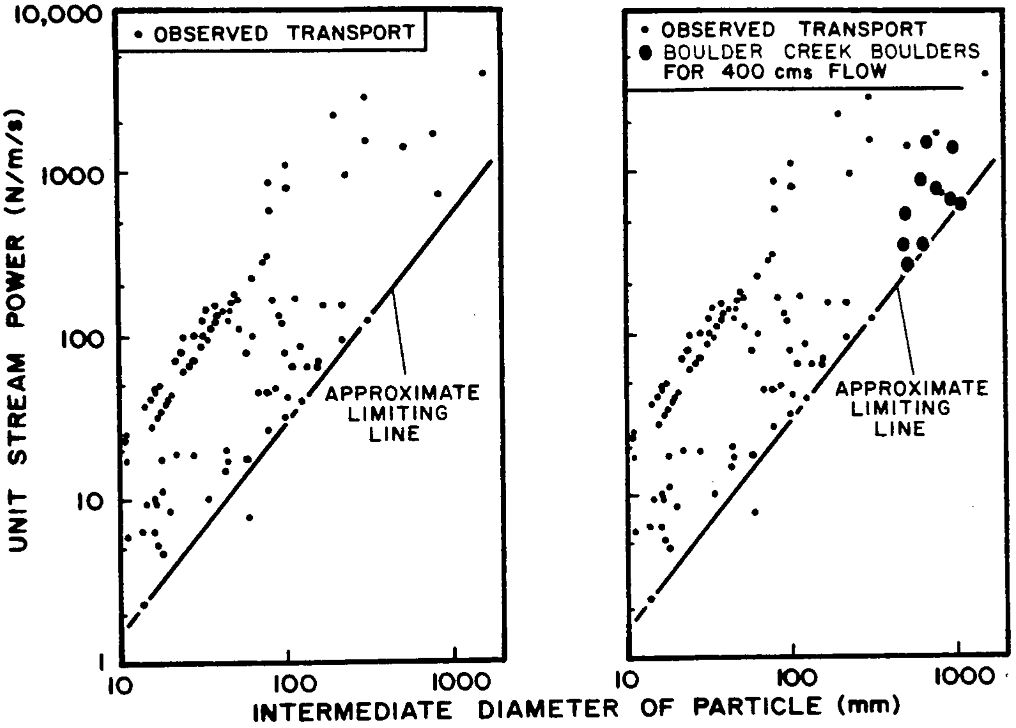

UNIT STREAM POWER (N/m/s)
10,000
1000
100
10
1
10
100
1000
• OBSERVED TRANSPORT
APPROXIMATE LIMITING LINE
• OBSERVED TRANSPORT
● BOULDER CREEK BOULDERS FOR 400 cms FLOW
APPROXIMATE LIMITING LINE
10
100
1000
INTERMEDIATE DIAMETER OF PARTICLE (mm)

TABLE 3. RIFFLE BOULDER MEASUREMENT DATA

RIFFLE	NUMBER OF BOULDERS MEASURED	AVERAGE INTERMEDIATE DIAMETER OF THE FIVE LARGEST BOULDERS (mm)	UNIT STREAM POWER* (N/M/S)
1	13	640	1440
2	11	1090	610
3	10	560	270
4	12	520	540
5	10	510	340
6	21	1010	1350
7	11	680	350
8	10	630	880
9	20	806	760
10	10	950	640

* 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 bankfull conditions.

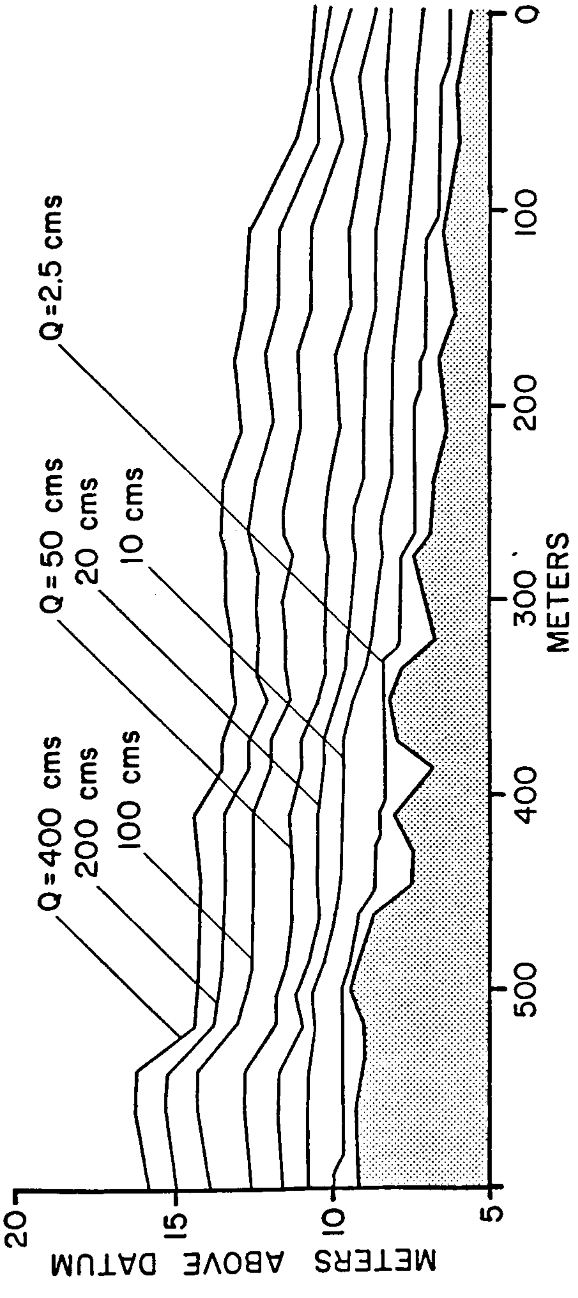
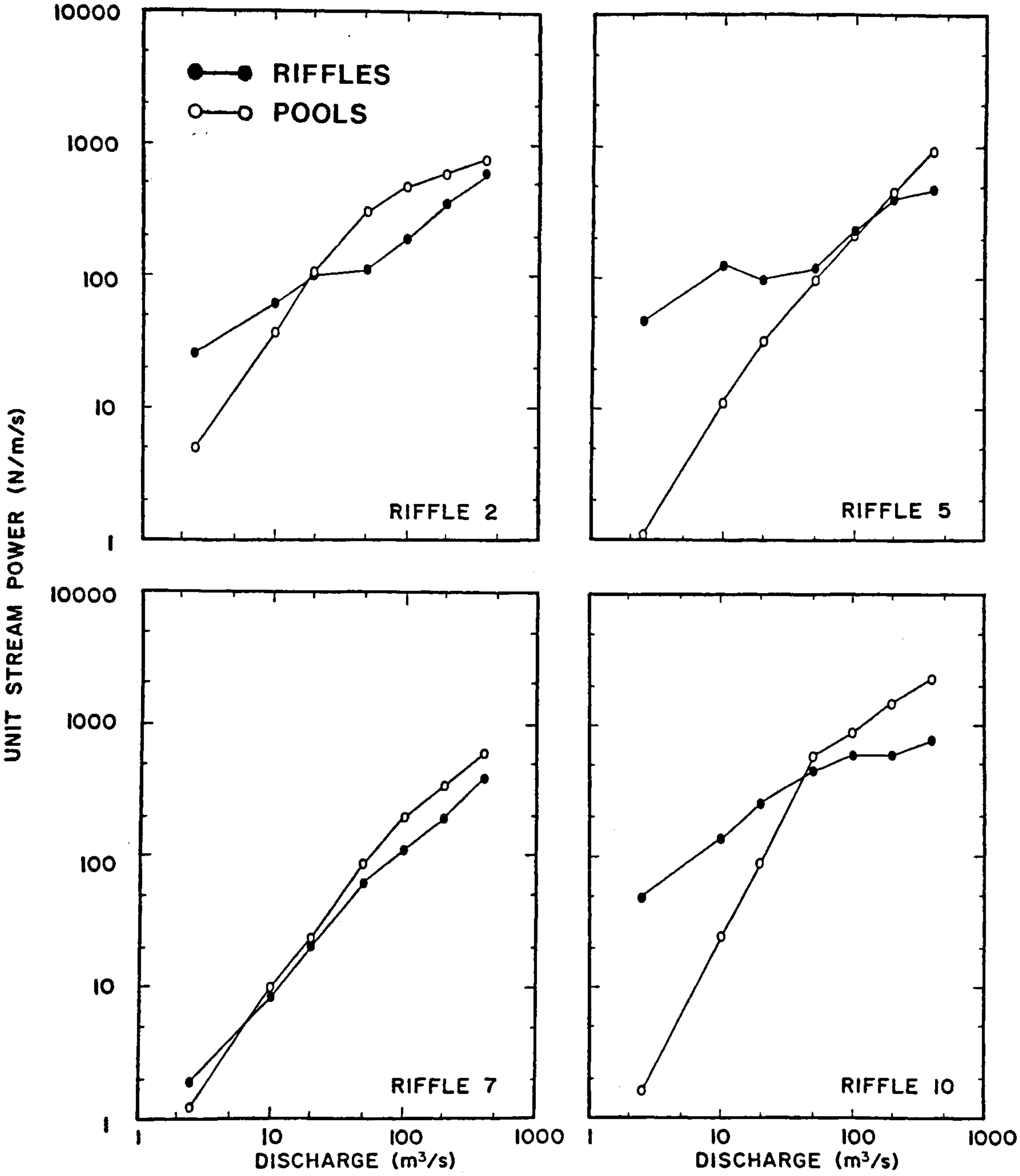

Q=400 cms
200 cms
100 cms
Q=50 cms
20 cms
10 cms
Q=2.5 cms
20
15
10
5
METERS ABOVE DATUM
0
100
200
300
400
500
METERS

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.

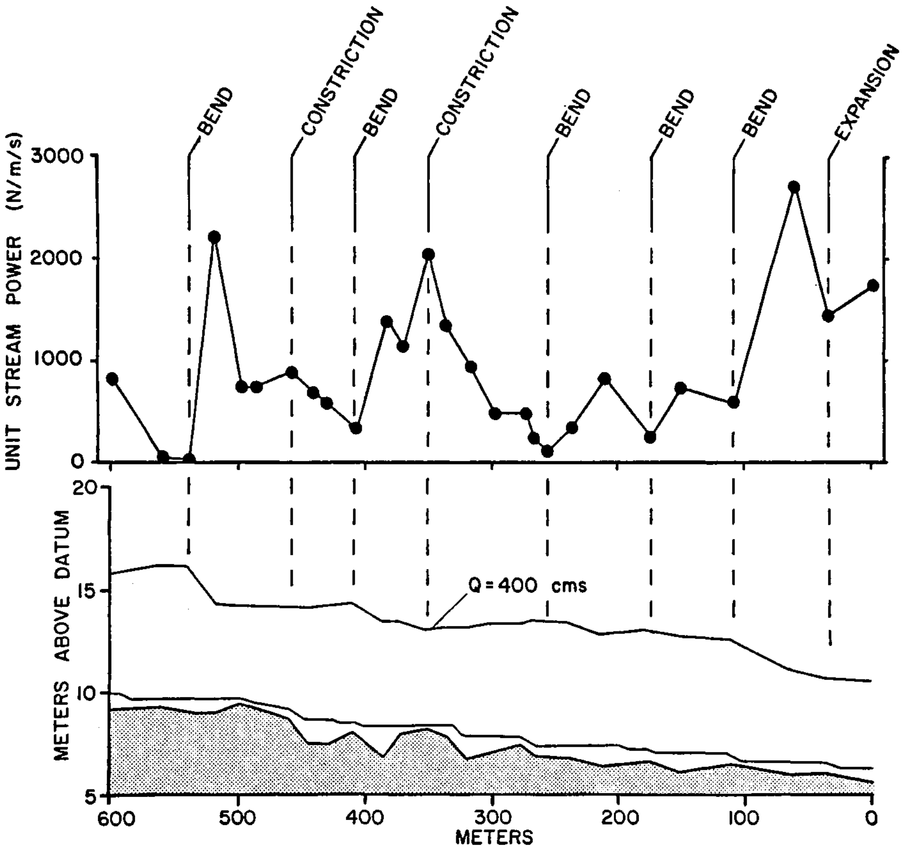

RIFFLES
POOLS
RIFFLE 2
RIFFLE 5
RIFFLE 7
RIFFLE 10
UNIT STREAM POWER (N/m/s)
10000
1000
100
10
1
DISCHARGE (m^3/s)
1
10
100
1000

A MODEL FOR BOULDER CREEK POOL AND RIFFLE PATTERN DEVELOPMENT

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.


BEND
CONSTRICTION
BEND
CONSTRICTION
BEND
BEND
BEND
EXPANSION
UNIT STREAM POWER (N/m/s)
3000
2000
1000
0
METERS ABOVE DATUM
20
15
10
5
Q=400 cms
600
500
400
300
200
100
0
METERS

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 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.

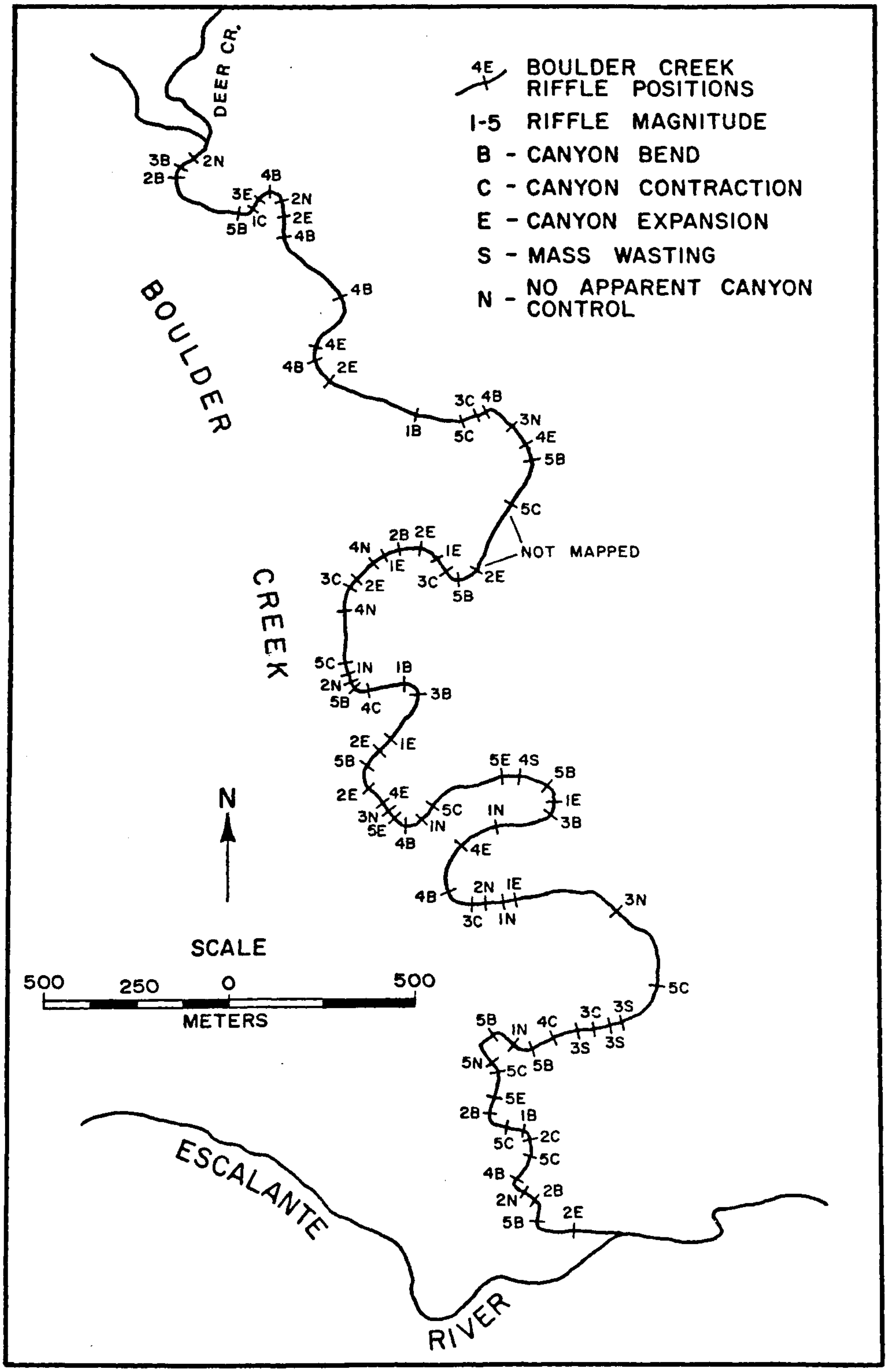
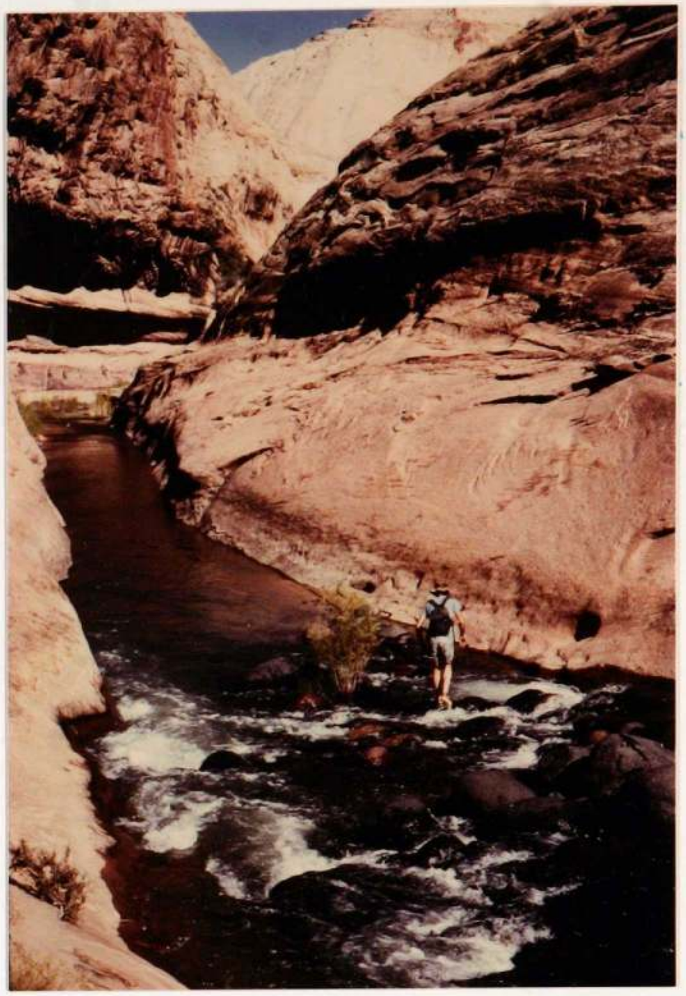
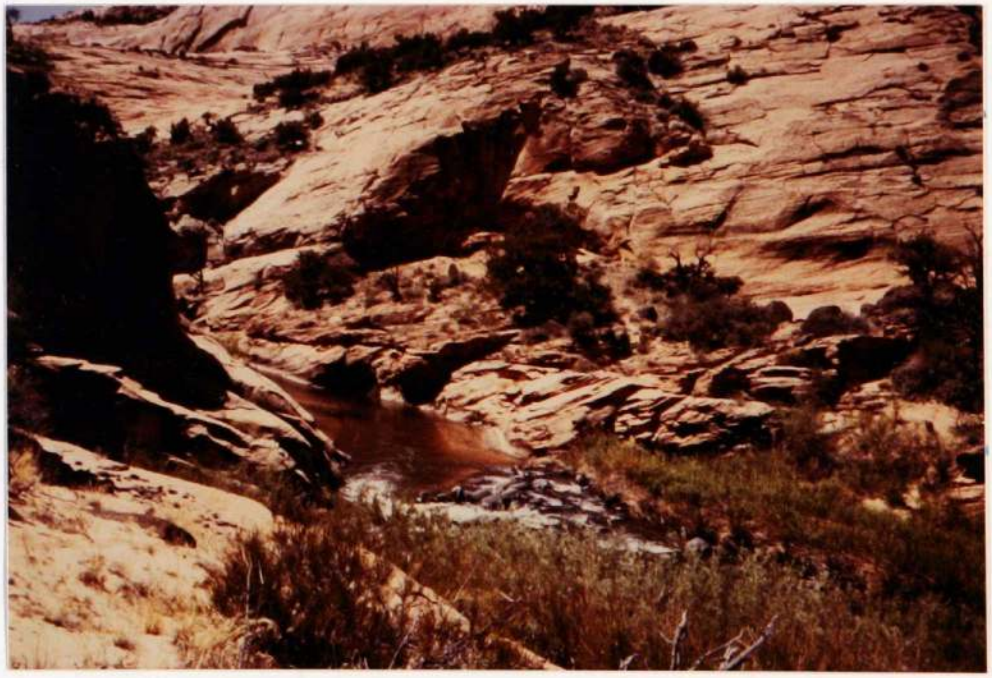

4E
BOULDER CREEK RIFFLE POSITIONS
1-5 RIFFLE MAGNITUDE
B - CANYON BEND
C - CANYON CONTRACTION
E - CANYON EXPANSION
S - MASS WASTING
N - NO APPARENT CANYON CONTROL
DEER CR.
BOULDER
CREEK
ESCALANTE
RIVER
NOT MAPPED
N
SCALE
500
250
0
500
METERS
3B
2N
2B
4B
3E
2N
1C
2E
5B
4B
4B
4E
4B
2E
1B
3C
4B
5C
3N
4E
5B
5C
2B
2E
4N
1E
1E
3C
2E
3C
2E
5B
4N
5C
1N
1B
2N
3B
5B
4C
2E
1E
5B
5E
4S
5B
2E
4E
1E
3N
5C
1N
3B
5E
1N
4B
4E
4B
2N
1E
3C
1N
3N
5C
5B
1N
4C
3C
3S
3S
3S
5N
5C
5B
5E
2B
1B
5C
2C
5C
4B
2B
2N
5B
2E

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.



A.



B.

TABLE 4. RELATIONSHIP OF BOULDER CREEK RIFFLE POSITIONS TO CANYON MORPHOLOGY

ASSIGNED MAGNITUDE	NUMBER OF OCCURRENCES				
	IMMEDIATELY UPSTREAM OF CANYON BENDS	IMMEDIATELY UPSTREAM OF CANYON CONSTRICTIONS	IMMEDIATELY DOWNSTREAM OF CANYON EXPANSIONS	MASS WASTING FROM BOULDERY TERRACES	NO APPARENT MORPHOLOGIC CONTROL
ONE	3	1	5	0	5
TWO	4	1	8	0	4
THREE	3	5	1	3	4
FOUR	8	2	3	1	2
FIVE	9	8	4	0	1

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".

ACKNOWLEDGMENTS

I am indebted to several individuals who have offered invaluable support to many facets of this project. Keith Katzer and Jon Shenk provided able help and expertise in the field. Helpful reviews of earlier drafts of this report were provided by V. R. Baker, W. B. Bull, E. M. Laursen, and S. Hecker. I especially appreciate the help of Robert H. Webb who provided assistance and guidance in many phases of the project, including suggesting the Boulder Creek study area.

Financial support for field work was provided by the Department of Geosciences of the University of Arizona, Sigma Xi, and the Geological Society of America (Hoover Mackin Research Grant). Radiocarbon analyses were financed in part by the United States Department of the Interior Geologic Survey through the States Water Resources Research Institute Program.

REFERENCES

Bagnold, R. A., 1966, An approach to the sediment transport problem from general physics: U. S. Geological Survey Professional Paper 422-I, 37 p.

_______, 1980, An empirical relationship of bedload transport rates in flumes and natural rivers: Proceedings of the Royal Society of London, A372, p. 453-473.

Baker, V. R., 1977, Stream-channel response to floods, with examples from central Texas: Geological Society of America Bulletin, v. 88, p. 1057-1071.

_______, Kochel, R. C., and Patton, P. C., 1979, Long-term flood frequency analysis using geological data: International Association of Hydrological Sciences, Publication 128, p. 3-9.

_______,_______,_______, and Pickup, G., 1983, Palaeohydrologic analysis of Holocene flood slack-water sediments: Special Publications of the International Association of Sedementologists, 6, p. 229-239.

Costa, J. E., 1983, Paleohydraulic reconstruction of flash flood peaks from boulder deposits in the Colorado Front Range: Geological Society of America Bulletin, v. 94., p. 986-1004.

Chow, V. T., 1959, Open-channel hydraulics: New York, McGraw-Hill, 680 p.

Dalrymple, T., and Benson, M. A., 1967, Measurement of peak discharge by the slope-area method: U. S. Geological Survey Techniques Water Resources Division, Book 3, Chapter A-2, 12 p.

Einstein, H. A., 1950, The bedload function for sediment transportation in open channel flows: Technical Bulletin No. 1026, U. S. Dept. of Agriculture, Washington, D. C., 71p.

Feldman, A. D., 1981, HEC models for water resources system simulation: theory and experience, in Chow, V. T., ed., Advances in hydrosciences: New York, Academic Press, p. 297-423.

Graf, W. L., 1979, Rapids in canyon rivers: Journal of Geology, v. 87, p. 533-551.

Hydrologic Engineering Center, 1979, HEC-2 water surface profile: Program Users Manual, U. S. Army Corps of Engineers, California, 39 p.

Keller, E. A., 1971, Areal sorting of bed-load material: the hypothesis of velocity reversal: Geological Society of America Bulletin, v. 82, p. 753-756.

Kochel, R. C., Baker, V. R., and Patton, P. C., 1982, Paleohydrology of southwestern Texas: Water Resources Research, v. 18, p. 1165-1183.

Lisle, T., 1979, A sorting mechanism for a riffle-pool sequence--summary: Geological Society of America Bulletin, v. 90, part 1, p. 616-617.

McFall, C. C., 1971, Geology of the Escalante-Boulder area, Garfield County, Utah: Utah Geol. and Mineral Survey Map 31.

Patton, P. C., Baker, V. R., and Kochel, R. C., 1979, Slackwater deposits; A geomorphic technique for the interpretation of fluvial paleohydrology, in Adjustments of the fluvial system: Dubuque, Iowa, Kendall/Hunt Publ. Co., p. 225-253.

Stewart, J. H., and LaMarche, V. C., 1967, Erosion and deposition produced by the flood of December, 1964, on Coffee Creek, Trinity County, California: U. S. Geological Survey Proffesional Paper 422 K, 22 p.

Richards, K. S., 1978, Simulation of flow geometry in a riffle-pool stream: Earth Surface Processes, v. 3, p. 345-354.

Webb, R. H., and Baker, V. R., 1984, Flooding and alluvial processes on the Escalante River, Utah [abs.]: EOS (American Geophysical Union Transactions), v. 65, p. 893.

Williams, G. P., 1983, Paleohydrological methods and some examples from Swedish fluvial environments, I--cobble and boulder deposits: Geografiska Annaler, 65A(3-4), p. 227-243.

Wolman, M. G., and Miller, J. C., 1960, Magnitude and frequency of forces in geomorphic processes: Journal of Geology, v. 68, p. 54-74.

APPENDIX A

CHANNEL HYDRAULICS FOR A 400 CMS DISCHARGE

SECTION	MANNING'S n	V (M/S)*	R (M)	γ (N/M^3)	STREAM POWER (N/M/S)
1	0.035	5.92	2.93	9800	1744
2	0.035	5.61	3.19	9800	1441
3	0.035	6.81	2.75	9800	2715
4	0.035	4.43	5.04	9800	608
5	0.035	4.47	3.00	9800	743
6	0.035	3.37	5.29	9800	265
7	0.035	4.69	3.27	9800	833
8	0.035	3.64	4.50	9800	353
9	0.035	2.59	5.52	9800	118
10	0.035	3.31	5.73	9800	245
11	0.035	3.98	3.95	9800	480
12	0.035	4.08	4.91	9800	480
13	0.035	4.98	3.93	9800	941
14	0.035	5.65	4.12	9800	1352
15	0.035	6.40	3.63	9800	2048
16	0.035	5.22	3.06	9800	1176
17	0.035	5.48	3.00	9800	1372
18	0.035	3.55	3.71	9800	343
19	0.035	4.33	4.40	9800	598
20	0.035	4.74	5.88	9800	706
21	0.035	4.98	4.25	9800	911
22	0.035	4.63	3.81	9800	764
23	0.035	4.47	3.43	9800	715
24	0.035	6.38	2.80	9800	2215
25	0.035	1.83	5.14	9800	39
26	0.035	1.99	6.06	9800	49
27	0.035	4.70	3.50	9800	843

* Obtained directly from step-backwater computed hydraulics