YDRAULIC AND SEDIMENT TRANSPORT INVESTIGATION
YAMPA RIVER
DINOSAUR NATIONAL MONUMENT
1983

WATER
RESOURCES
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WRFSL Report No. 83-8

NATIONAL PARK SERVICE
Department of the Interior

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Hydraulic and Sediment Transport Investigation
Yampa River
Dinosaur National Monument
1983

FINAL REPORT

WRFSL Report No. 83-8

Submitted to:

United States Department of the Interior
National Park Service
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and
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April 1984

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The field study team consisted of Mr. Donald O'Hara, Mr. Michael Goldscheitter, Ms. Catherine Berry, and Ms. Karmen Kelly. Geology sections of this report were contributed by Mr. Goldscheitter. Dr. Ray Herrmann, Dr. E. V. Richardson, Dr. Marshall Flug, and Mr. Gary Smillie, participated in lengthy discussions over the technical aspects of the project. Mr. John Elliott was very helpful in providing necessary data. A special note of thanks is extended to all the above people in appreciation of their time, energy and patience.

INTRODUCTION

This report is the culmination of two years of sediment transport and river morphology investigation of the Yampa River in Dinosaur National Monument. The purpose of this study was to define a minimum streamflow which will preserve the processes and natural conditions vital to the channel morphology and aquatic life system of the river. The proposed minimum streamflow was prepared in the form of a seasonal hydrograph which includes the constraints imposed by sediment deposition in the canyon, fishery habitat, riparian vegetation, and other ecological considerations.

The Yampa River is the last remaining major free flowing tributary of the Colorado River system. In 1938 the Monument was enlarged to preserve the unique land and water resources associated with the incised meanders and desert plateau country of the Green and Yampa Rivers. Now the river flows forty-five miles through Dinosaur National Monument before joining the Green River near the Colorado-Utah border. To further protect and maintain the water and related resources of the Yampa River the National Park Service, Department of the Interior, initiated this minimum streamflow study.

Hydraulic and sediment transport data were collected during the spring and summer high flow periods of 1982 and 1983. Athough stream channel data was collected throughout the Yampa Canyon, all of the sediment data was collected at a site in a cobble substrate reach of the river. This four mile cobble bed reach is a unique substrate reach in the Yampa River system and is an observed spawning area for the endangered Colorado squawfish.

The report describes the field sampling program, data collection methods and results. A computer program was developed to model a portion of the cobble substrate reach. The computer model simulated the sediment transport, deposition and scour in response to different discharge hydrographs. In this manner a minimum streamflow hydrograph was designed to insure minimal sand deposition on the cobble substrate.

SPECIFIC RESEARCH OBJECTIVES

The comprehensive objective of this study is to quantify, through the understanding of hydraulic and sediment transport phenomena, a minimum streamflow hydrograph that will preserve and maintain, on an annual basis, the natural conditions and processes vital to biological system of the Yampa River in Dinosaur National Monument. This hydrograph would be sufficient to minimize any adverse impacts arising from a reduced or otherwise altered seasonal stream discharge. The specific requirements to accomplish this overall study objective are:

1) Define the natural conditions of the cobble bed reach in the canyon including the hydraulic, sediment transport, substrate and channel morphological conditions.

2) Establish a sediment transport rating curve in the cobble substrate river reach.

3) Relate hydraulic and sediment transport data collected in the Yampa Canyon at Mathers Hole and river mile 16.5 to the upstream gaging stations.

4) Mathematically simulate the observed flow conditions and sediment transport for the 1983 runoff season.

5) Predict the minimum streamflow hydrograph which will sustain a range of natural conditions and processes vital to the riparian ecology in the cobble bed reach.

After the investigation was initiated the following additional objectives were appended to the original proposal:

1) Perform a physical model study to calibrate the Helley-Smith bedload sampler. This flume investigation would also define the phenomena of sand transport over cobble substrate.

2) Describe the morphological characteristics of the observed Colorado squawfish spawning reach.

3) Determine the range of discharges that are required to preserve the morphological conditions that were observed or projected to have existed during the 1981-3 Colorado squawfish spawning periods.

The report describes how these objectives were accomplished. Background information is provided to acquaint the reader with the morphology and geology of the Yampa River Canyon. In addition, the methods of field data collection and sample analysis are discussed. The results have been divided into several sections including; historical flow, sediment transport, and physical and mathematical modeling. Additional detailed information on some technical aspects of the investigation are provided in the appendices.

BACKGROUND

Yampa River Geography and Geology

Dinosaur National Monument is in the northwestern and northeastern corners of Colorado and Utah, respectively. It lies between Craig, Colorado and Vernal, Utah. The monument is about 70 miles long (east to west), and ranges from 10 to 25 miles wide (north to south).

The Yampa River headwaters in the White River National Forest on the western slope of the Rocky Mountains near Yampa, Colorado. The Yampa flows north, then west joining the Green River in Dinosaur National Monument (see Figure 1). It is the Green River's largest tributary and drains approximately 7600 square miles before entering the Monument.

An average 1.5 million acre feet of water flow through the Monument each year in the Yampa, contributing on the average 1.5 to 2.0 million tons of sediment per year. Almost all of the sand sediment load is

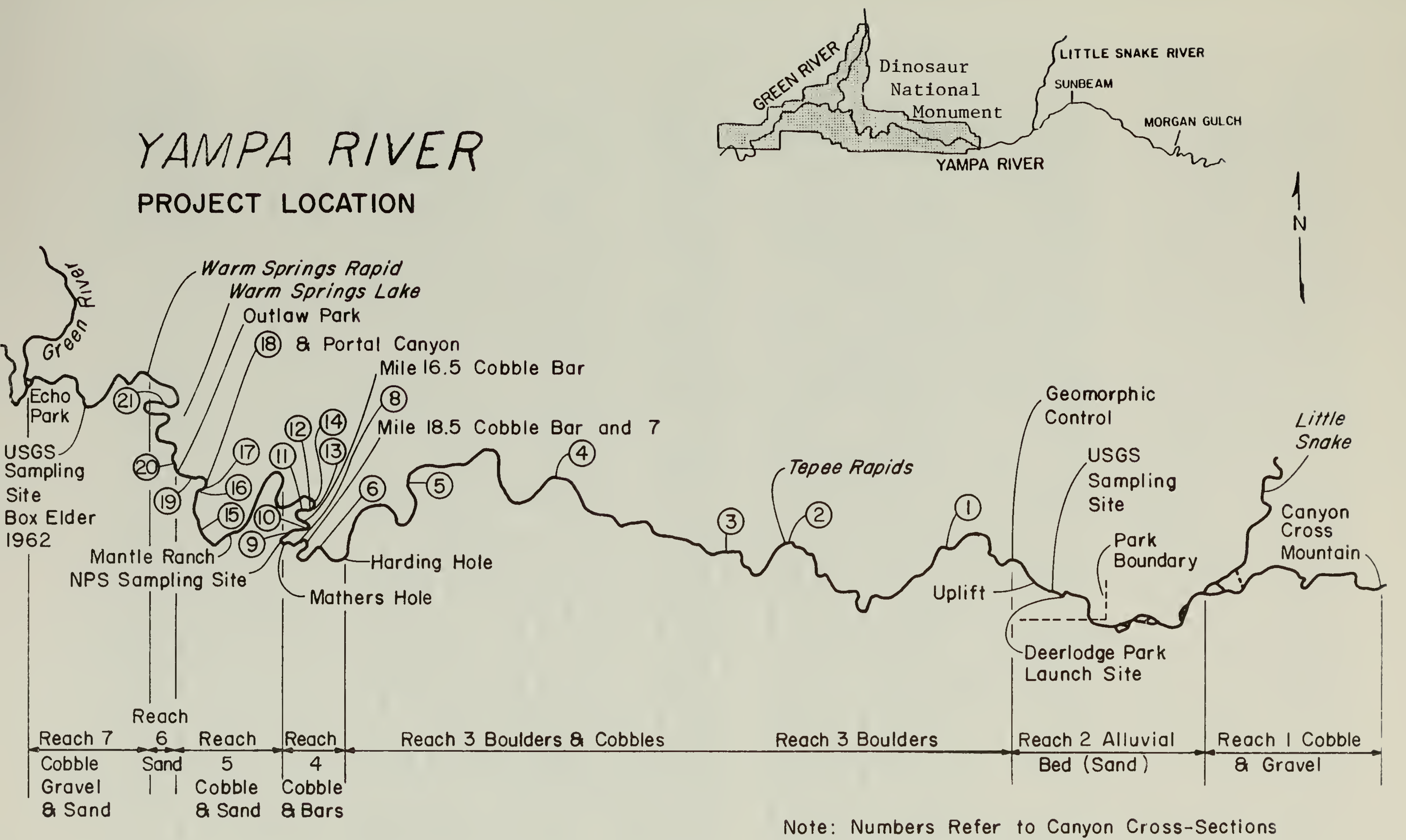

YAMPA RIVER
PROJECT LOCATION
GREEN RIVER
Dinosaur National Monument
LITTLE SNAKE RIVER
SUNBEAM
MORGAN GULCH
YAMPA RIVER
N
Green River
Warm Springs Rapid
Warm Springs Lake
Outlaw Park
18 & Portal Canyon
Mile 16.5 Cobble Bar
8
Mile 18.5 Cobble Bar and 7
Echo Park
USGS Sampling Site
Box Elder 1962
21
20
19
17
16
15
12
14
11
13
10
9
6
5
4
3
2
1
Mantle Ranch
NPS Sampling Site
Harding Hole
Mathers Hole
Tepee Rapids
Uplift
Geomorphic Control
USGS Sampling Site
Park Boundary
Deerlodge Park Launch Site
Little Snake
Canyon Cross Mountain
Reach 7 Cobble Gravel & Sand
Reach 6 Sand
Reach 5 Cobble & Sand
Reach 4 Cobble & Bars
Reach 3 Boulders & Cobbles
Reach 3 Boulders
Reach 2 Alluvial Bed (Sand)
Reach 1 Cobble & Gravel
Note: Numbers Refer to Canyon Cross-Sections

Figure 1

delivered by the Little Snake River entering the Yampa just four miles east of the Monument Boundary. This sediment load is transported through the cobble substrate reaches in the lower half of the canyon.

Dominating the landscape of Dinosaur National Monument are the Green and Yampa River canyons. Both rivers have been entrenching into bedrock since late Cretaceous time, about 70 million years (m.y.) ago. Prior to that time they were meandering rivers flowing on a mature plateau. The rivers still meander, but have incised within steep-walled canyons.

The mechanics of meander entrenchment are not clearly understood, but W. R. Hansen has a good theory for incisement of the Green River (1969, and personal communication, 10/7/83). He postulates that the Lower Green originally flowed from Browns Park into the North Platte River on the then-developing Browns Park Formation. Sediments and volcanic ash were accumulating to a thickness of over 7,000 feet. Between the Uinta and Yampa Faults the eastern part of the Uinta Mountains was collapsing. The Browns Park Formation overtopped the valley rim, and the Green River breached the Uinta crest at the present site of Lodore Canyon. The river cut quickly through the soft Browns Park formation to harder rocks below. The main Green was still flowing eastward across the rising Continental Divide. The Lower Green incised itself to its new base level, and eventually captured the main Green and turned it south. The Yampa River appears to have a similar history of incision into the Browns Park formation.

The Yampa canyon profile varies distinctly between reaches with different rock lithologies. Two formations are seen most often in the canyon, the Morgan and the Weber. The Morgan consists mainly of limestone beds and underlies the Weber. The Weber is a relatively soft sandstone.

Where the Yampa flows through the Morgan, the valley profile tends to be asymmetrical. On the south side steep walls are found, while the north side slopes gently and is covered with talus. The asymmetry is caused by lithology and by the dip of the beds, which is 7 to 10 degrees to the southwest. The lower member of the Morgan is an incompetent shale, which rests on the Round Valley Formation, a limestone. Where exposed by the river the shale slides on the Round Valley downslope, causing overlying rocks to collapse. Most landslides therefore occur on north slopes, in the Morgan. The river channel is confined between the steep talus slopes and has no floodplain. Channel location in the valley has been dictated in some reaches by the ancient landslides.

In the Weber formation the canyon's profile is symmetrical. The Weber is a soft sandstone which is easily eroded by the river. Smooth, curving walls are often vertical or past vertical depending on the length of time they are subjected to the erosive forces of the river.

Channel bed slope varies with rock type encountered. In the upper reach of the canyon, the slope is steep where the river flows through the Morgan. Boulders and talus from slides armor the river bed slowing its rate of downcutting through the hard limestone formation. The slope is steeper than in the reach where the softer Weber Sandstone is the controlling formation. Here the river often directly attacks the bedrock, which it erodes easily. The rate of downcutting in the Weber decreases as the channel elevation approaches the Green River base level (Figure 2).

Site Description

River Mile 16.5

Three study sites were selected in the cobble bed reach of the Yampa River. River mile 16.5 and 18.5 were chosen for hydraulic investigation of the cobble substrate. Hydraulic and sediment transport data were collected at the Mathers Hole site located between the other study sites. A description of the sites follows.

The cobble bar at river mile 16.5 is a large cobble and sand longitudinal bar (approx. 900 ft. long and 300 ft. wide). It splits the main channel into two smaller channels (or three at high flows—see Figure 3). The Weber Sandstone is exposed through the entire cobble bar reach, attaining a maximum thickness of about 700 feet on the left bank. Talus and soil is found at wall bases and supports grasses, junipers, and box elders. The Weber is poorly consolidated and thus easily eroded, forming steep, smooth, curving walls. On the left bank is a vegetated flood terrace which extends to the midpoint of the cobble island, where it meets Weber talus and some sand.

Appearing below cross-section 4 (Figure 3), on the right bank, is a limestone bed in the Morgan Formation (lower Pennsylvanian). It dips upstream at about 6°, rises through the remainder of the section, and is about 10 feet thick. The outcrop does not become prominent until about 80 feet above cross-section 2. This outcrop is far more erosion-resistant than the Weber Sandstone, and extends into the channel rather than being sharply cut off. Here it accumulates muds and supports algae. On the left bank only a small portion of the limestone is seen, just above cross-section 1, but it quickly disappears under talus.

The bed material is essentially cobbles from cross-section 1 to 5, with exception of the large pool in the left channel near cross-section 2 which consists of sand and boulders and a large portion of the right channel which is small boulders from the talus slope. Cross-sections 6 through 8 constitute a pool reach with a large percent of the substrate being sand. The pool is at cross-section 7 is deep with large submerged boulders. The riffle extends from cross-section 5 to cross-section 1 and includes both channels.

River Mile 18.5

At river mile 18.5 is another cobble, riffle reach which is similar to that at mile 16.5. A longitudinal bar of cobbles and sand splits the main channel into two subordinate channels (Figure 4). The Weber Sandstone is exposed through this reach with no trace of the Morgan Formation. As with the site at mile 16.5, an overhanging ledge is found at mile 18.5. It rises from the water about 50 feet below the uppermost point of the bar, and continues to rise throughout the remainder of the

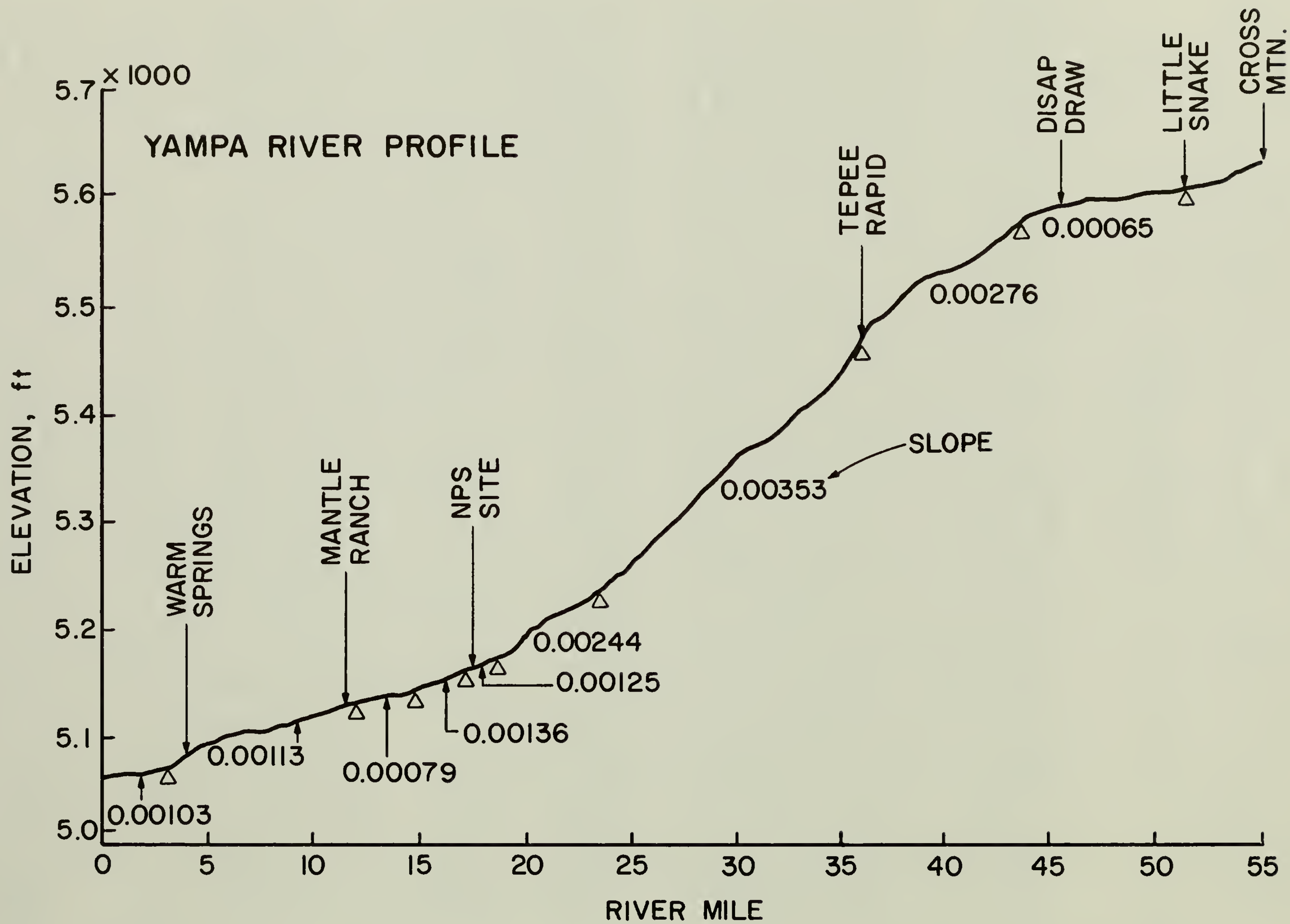

YAMPA RIVER PROFILE
ELEVATION, ft
× 1000
5.7
5.6
5.5
5.4
5.3
5.2
5.1
5.0
0
5
10
15
20
25
30
35
40
45
50
55
RIVER MILE
WARM SPRINGS
MANTLE RANCH
NPS SITE
TEPEE RAPID
DISAP DRAW
LITTLE SNAKE
CROSS MTN.
SLOPE
0.00103
0.00113
0.00079
0.00136
0.00125
0.00244
0.00353
0.00276
0.00065

Figure 2

YAMPA RIVER SPAWNING REACH RIVER MILE 16.5 AT 1000 CFS ON AUG. 11, 1983

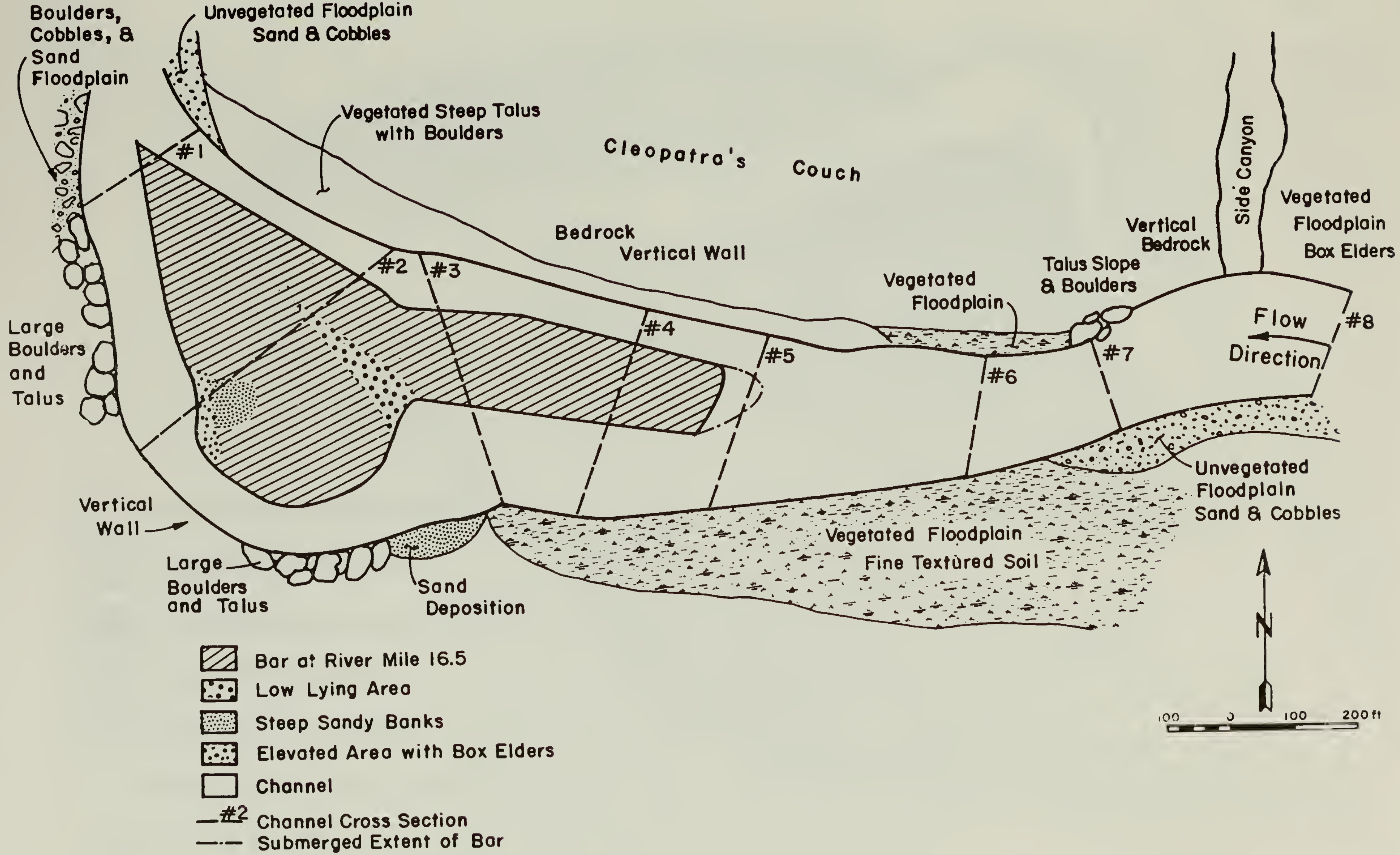


Figure 3

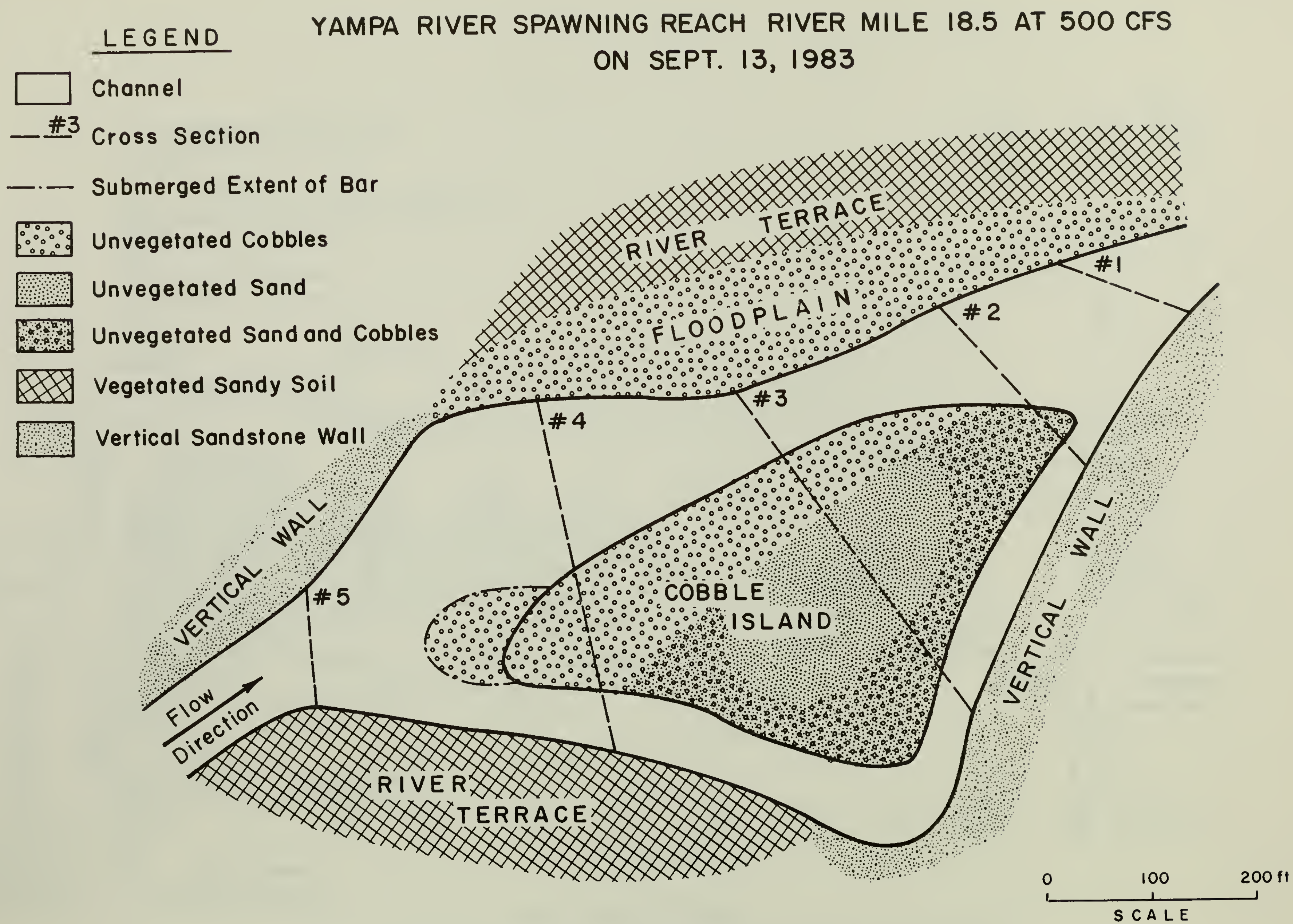

YAMPA RIVER SPAWNING REACH RIVER MILE 18.5 AT 500 CFS
ON SEPT. 13, 1983
LEGEND
Channel
#3 Cross Section
Submerged Extent of Bar
Unvegetated Cobbles
Unvegetated Sand
Unvegetated Sand and Cobbles
Vegetated Sandy Soil
Vertical Sandstone Wall
RIVER TERRACE
FLOODPLAIN
#1
#2
#3
#4
#5
COBBLE ISLAND
VERTICAL WALL
VERTICAL WALL
Flow Direction
RIVER TERRACE
0
100
200 ft
SCALE

Figure 4

stretch. Instead of limestone, however, the rock is Weber Sandstone, which is easily eroded. Water diverted around the cobble bar flows with against this outcrop and has formed on overhang of about 25 feet. On the underside of the ledge moss grows, and is fairly thick and lush near the water surface at the upstream end.

Most of the river flow passes through the left channel thalweg. At high flow the cobble island is completely submerged. Cross-section 5 is a deep pool with a sand substrate. The riffle initiates at cross-section 4 and extends to cross-section 2. Cobble substrate is found in both channels in the riffle with large cobbles and small boulders comprising the bed material in the left channel near cross-section 3. Both the cobble bars at river mile 16.5 and 18.5 are constructed of cobbles deposited in a flow expansion. The cobble bar at river mile 18.5 has considerably more sand covering the cobbles when exposed at low flow than at river mile 16.5.

Mathers Hole, River Mile 17.5

Mathers Hole is located between the two previously described sites. It was established in a mild sloped reach of the river, which is partially armored with cobble substrate. Cobble bars or islands are located immediately upstream and downstream, dividing the flow and creating riffles where it is constricted between the islands and bedrock walls. This recurring riffle-pool sequence constitutes a reach of the Yampa River from river mile (RM) 16.5 to 20.5. Cobbles bars or islands have developed just upstream of each incised meander bend where the channel widens. The river is described as a wide bend, point bar stream with a distinct riffle-pool sequence.

The site is reasonably straight with a short longitudinal cobble bar that becomes exposed at low flows. The left bank is a vertical Weber Sandstone wall, six hundred feet high. The right bank is a vegetated terrace rising approximately twelve feet above the cobble substrate. The river has entrenched a channel below this bench which is very stable up to bankfull discharge. The thalweg is permanently located near the left bank. During peak flows the water surface slope is uniform for several river widths downstream. A riffle-pool sequence develops with dropping stage and the water surface slope through the site is reduced.

DATA COLLECTION

Field Techniques

Sediment discharge measurements were collected at Mathers Hole. These measurements constitute the sediment supply to the cobble substrate reach at river mile 16.5. Hydraulic measurements were made at cross sections established at river mile 16.5 and 18.5. Twenty-one additional cross sections were established at various sites in the canyon. These cross sections were monitored early in the spring during the rising limb and again, late in the fall as the discharge approached baseflow.

In 1982 nine hydraulic measurements and sediment samples were collected at Mathers Hole in the months May through July. The seasonal hydrograph was composed of two peaks; the first of which occurred on May 5 and was the highest. All the sediment samples were collected on the recessional limb. The highest measured discharge for which samples were collected was approximately 11,000 cfs.

The sampling program for 1983 was greatly expanded over that from the previous year. Forty-three daily sets of sediment data were collected at Mathers Hole, with the highest sampling discharge being 19,300 cfs. Measurements were made on both the rising and recession limbs; 28 sets of sediment data were collected on the rising limb and 15 on the falling limb. The sediment samples were supplemented with measurements of water surface slope, river width, cross section profiles and velocity.

Suspended sediment samples were collected at ten foot verticals with a USGS D-74 depth integrating suspended sediment sampler using the ETR (Equal Transit Rate) method. The D-74 sampler is lowered from the surface to bed and raised to the surface at the same rate at each vertical. This rate should not exceed that which would fill the bottle approximately three quarters full at the deepest vertical. The transit rate is established by volume of sampler container, nozzle size, velocity profile of the stream, and the flow angle. A type B-56 USGS reel was used to raise and lower the D-74 sampler.

In 1982, a sample bottle was collected at each vertical and returned to the laboratory for analysis. An improved and simplified method was implemented for 1983 field season. After the bottle was removed from the suspended sampler, the contents were poured through a 0.0625 mm sieve into a graduated cylinder and the volume recorded. The fluid contents plus the fine sediment (silts and clays) were then poured into a 32 liter churn. This process was repeated at each ten foot vertical for two crossings of the entire river. At the completion of each crossing the sand size sediment in the sieve was washed into a container and sealed. Following the completion of the second crossing, the churn was pumped and three supernatant samples were drawn off from the nozzle of the churn into three separate 250 ml bottles. These bottles together with the two sand containers were returned to the laboratory to determine suspended sediment concentration. The field assistants were trained by USGS personnel in Denver to apply this new method.

The Helley-Smith sampler was employed to collect unmeasured sediment zone samples near the bed. The Helley-Smith sampler was operated at each vertical in conjunction with the D-74 sampler. At each vertical, the Helley-Smith sampler was lowered to the bed and left there for 30 seconds. For each crossing a separate bag of sediment was collected, sealed and returned to the lab. The Helley-Smith sampler is not sanctioned by the USGS but represents the best available technology for bedload and unmeasured suspended zone sampling.

Discharge measurements were facilitated in 1983 by erecting a staff gage. A stage-discharge relationship was calibrated with 24 measurements over the two field seasons. The Mathers Hole cross section becomes a more effective conveyor of discharge at higher stages which results in the nonlinear stage-discharge relationship shown in Figure 5. Discharge was measured from 600 cfs to 19,000 cfs to define the relationship.

Velocity was measured with the Price current meter or the Price pygmy meter in all facets of the project. The average velocity for each ten foot cell was taken at the 0.6 depth below the water surface. Several vertical velocity distributions were plotted to check the reliability of 0.6 depth measurement. In several instances velocity measurements were taken at 0.2 and 0.8 depth interval to improve the accuracy of the measurements.

Substrate analysis was accomplished with a probe. The composition was verified at low flow by observation of the exposed channel and by walking the cross section at shallow depths. Numerous photographic analyses were made with a calibrated square. These photographs were evaluated with collected surface and subsurface substrate samples at several cross sections on the spawning bar (Photo 1).

Cross section profiles were made with a continuous sonar depth chart recorder. The profiles were calibrated by surveying the end points. All cross section profiles in the canyon and at the spawning bar sites were obtained in this manner.

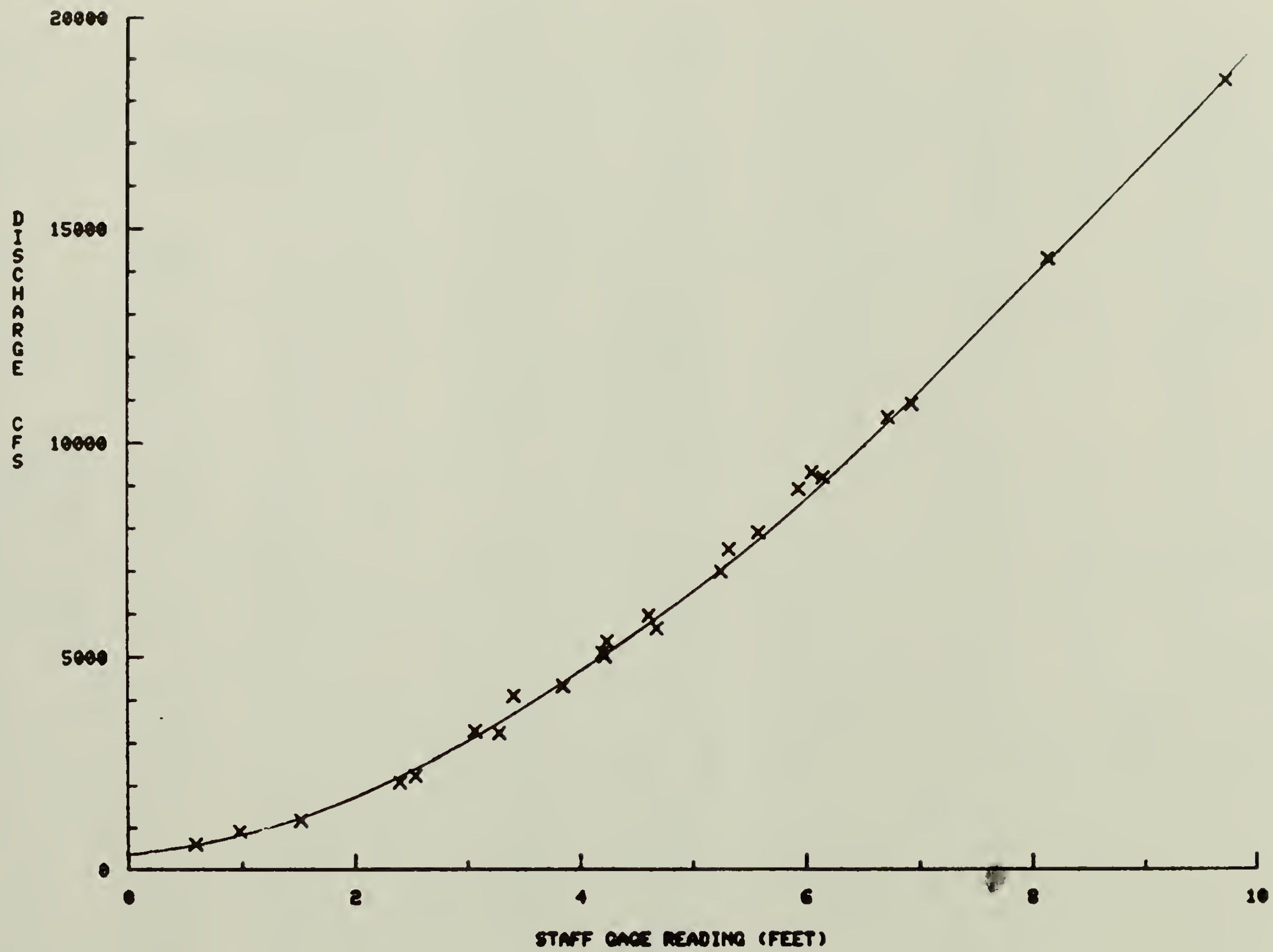
Water surface slopes and cross section references points were surveyed. The slopes were measured, where possible, several river widths upstream and downstream. It was impossible to measure water surface slope at several cross sections during peak flow.

Twice, during the high discharges near the peak, equipment failures resulted in abandoning the data collection for that particular trip. Of the forty-three sets of sediment samples, forty-two Helley-Smith samples were collected and thirty-nine sets of suspended sediment were separated into fine sediment and sand splits.

At river mile 16.5, eight cross sections were set up for hydraulic data collection. One set of data at each cross section was taken in April, three additional sets were taken in July and August. Five cross sections were established at a replicate site, river mile 18.5. These were monitored three times during the recessional limb, just one or two days prior to the measurements at river mile 16.5. Water surface slope, velocity, depth, and substrate data were collected at both sites. This data was reduced and prepared as input to the U.S. Fish and Wildlife Service physical habitat simulation computer model (PHABSIM).

Laboratory Analysis

The mesh size of Helley-Smith sampler bag is 0.25 mm. When determining the total unmeasured zone load and corresponding size distribution, the particle sizes less than 0.25 mm were first removed from the sample. All samples were dried, weighed and sieved at the CSU Engineering Research Center soils laboratory. The suspended sediment sand splits were similarly dried and weighed. A USGS standard visual accumulation tube was employed to obtain size distribution of each suspended sample.



STAGE - DISCHARGE RELATIONSHIP MATHERS HOLE 1982 & 1983

Figure 5

Photo 1. Cobble Substrate at River 16.5

The fine suspended sediment (≤0.0625 mm) was analyzed for concentration. Each set of three bottles of supernatant was filtered through a pair of Millipore filters preweighed to the nearest ten thousandth of a gram. The dry filter pairs were placed in a Gelman filter funnel and the contents of the 250 ml supernatant bottles were poured into the funnel. A vacuum pump assisted the filtering process. The concentration of each of the three bottles was calculated by determining the weight of fines on the filter, weight of the supernatant sample, and correction factor obtained from the second filter.

Additional laboratory analyses included measurement of cobble sizes captured in the Helley-Smith sampler, size distribution of bed material, photographic analysis of bed material and analysis of the sonar depth chart recordings.

RESULTS AND DISCUSSION

Yampa Canyon Morphology

The Yampa River canyon incised meanders are the dominant physical feature in the plateau topography. This unique physical environment creates a diverse biological habitat. Complex relationships exists between the aquatic species and the habitat created by the river. Response of the physical system to changes in flow regime would disturb the stable, equilibrium conditions which support the river ecosystem. The channel morphology and aquatic environment is a function of several interrelated physical features of the system including geology, climate, basin size, topography, sediment transport and others. The following discussion will focus on the important aspects which define the range of natural conditions and processes that exist in critical or sensitive habitat reaches of the Yampa River.

The incised meanders have an average wavelength of approximately 0.62 miles. The original formative discharge for producing the paleochannel meanders with a wavelength of 0.62 miles is approximately 10,500 cfs. This is derived from empirical relationships of existing rivers (Richards, 1982). The corresponding width is about 250 feet or equal to present day width. Over geologic time the annual discharge has increased. As the river incised in bedrock, the base level dropped, increasing the drainage basin and the annual discharge.

Every river system evolves in a manner that establishes approximate equilibrium between the channel and the water and sediment it conveys. The reaches in the canyon comprise a long profile shown in Figure 2 which reflects the long term evolution on geologic temporal and spacial scales. The slope-substrate-discharge relationship is complicated. Size of the bed material is proportional to the depth and slope, and generally, a milder slope will result in a smaller substrate. In the upper reaches of the canyon, downcutting is inhibited by the large substrate and the erosion resistant formation. The downstream decrease in bed material sizes is the result of sorting as a function of slope. Abrasion accounts for some of the downstream size reduction.

The river contacts the Weber sandstone in the lower portion of the canyon. In many areas the river flows directly on the sandstone bedrock which is soft and easily eroded. As the Green River confluence approaches the river slope becomes more mild. Reaches of cobble substrate have evolved into a riffle-pool sequence in this section. The very mild sloped portions have a sand and gravel substrate. In contrast, the initial twenty-five miles of canyon, are uniformly steep punctuated by rapids and corresponding backwaters formed by side canyon flood events.

The river is characterized in the cobble substate reach as a wide bend, point bar stream with a distinct riffle-pool sequence. The wider bends are the remanents of the meandering paleochannel whose pattern was partially preserved in the structure of incised bedrock canyon. The Yampa riffle-pool sequence is not typical of a natural meandering river because of the bedrock controls. Riffle spacing is normally five to seven times the channel width, but riffles have developed in the Yampa wherever channel expansions have occurred; most often just upstream of wide bends.

The long term development of the shape, size and orientation of cobble bars and islands in this reach has been a gradual process starting with initial formation of meander incision. Over geologic time a sequence of large, infrequent disharges contribute to the progressive downstream movement of the cobbles. The riffle-pool sequence evolves as a function of the large discharges; the cobbles tending to pile up in the flow expansions upstream of bends. The riffle is initiated by the leading edge of the depositional region. In this fashion, the bar or island stability has been established on a quasi-permanent scale with lesser discharge events inciting limited cobble motion.

Maintenance of channel dynamic equilibrium requires progressive adjustment of slope and spatial variation. Bars tend to be energy dissipating structures that promote overall channel stability. Energy expediture per unit bed area is equalized with mobilization of cobbles and localized width and depth adjustment. Channels around cobbles bars are reformed with failing side slopes and changing widths. At peak flows vertical accretion of the cobble bar is an example of depth adjustment. Such accretion, forces additional flow to impinge on the banks and create side channels of high velocity and unstable beds.

The large sediment load in the Yampa River is supplied principally by the Little Snake River. Sufficiently steep slopes and velocities insure that the sediment is transported without significant deposition in the canyon. Pool reaches often have a sand substrate which degrades during peak discharges. Cobble substrate riffles remain essentially free from sand deposition in spite of the large sediment load. The processes which insure a sand free cobble substrate are closely linked to a seasonal hydrograph in terms of shape and duration.

Historical Flow and Flood Frequency Analysis

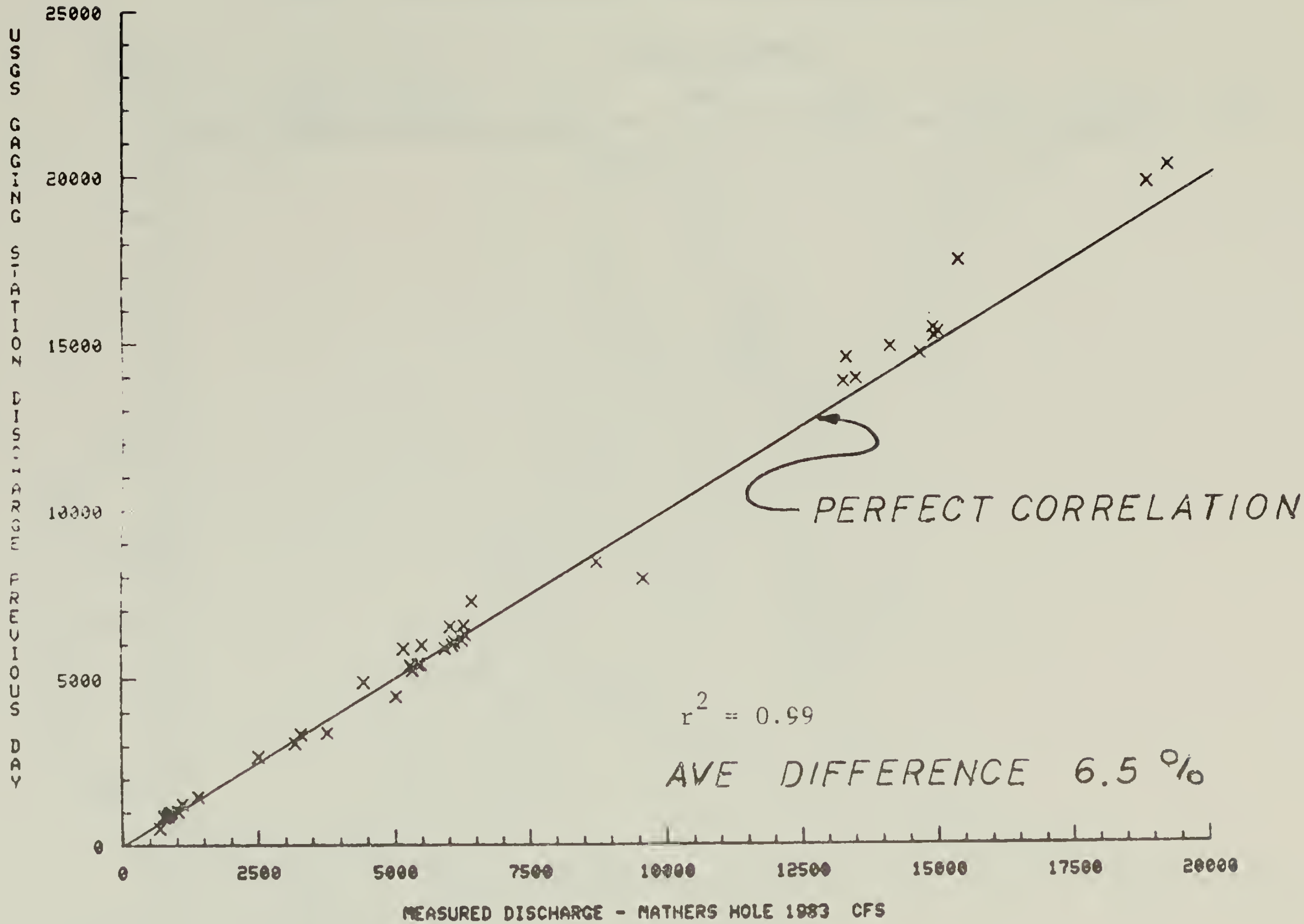
USGS gaging stations are located at Maybell on the Yampa River and Lilly on the Little Snake, approximately 40 and 15 miles upstream of Dinosaur National Monument, respectively. No substantial tributary inflow or stream losses occur in the intervening reach and therefore, the gaging station flows represent the inflow to the Monument. On the average, the USGS discharge computed by combining the discharge at the stations is slightly higher than that discharge measured at Mathers Hole (see Figure 6). This comparison is only relative, however, being a function of the flow travel time, the time of day that the discharge measurements are made and the magnitude of the unsteadiness of the flow. The average difference of 6.5% (absolute) between the discharges gives credibility to stage-discharge relationship at Mathers Hole.

The 1983 Yampa River discharge and the mean annual discharge are shown in Figures 7 and 8. The mean annual discharge was calculated using the period 1941-83. The period from 1922-83 constitutes the entire period of record. The first 20 years of this record were wetter than the remaining 40, and the 1941-83 period is more representative of the conditions that exist today in the Yampa River (USGS, John Elliott, personal communication, 2/83). Table I reveals the marked difference between the periods. The lower discharge period, 1941-1983, has a mean water yield of 1,483,700 acre-feet, compared to 1,508,400 acre-feet for the entire period of record.

Figures 9 and 10 are plots of the five and ten year running average of the annual volumes of the Yampa River at Deerlodge. The climate was drier than normal from about 1935 through 1965. The 1920's and 1965-1975 are wet periods which offset the dry period in the 1930's and 40's. The period of record is too short to discern any distinct cycles. The sediment record for the Little Snake, however, occurs during a drier than average period. It is difficult to speculate on the relative magnitude of sediment yield during dry or wet periods but generally, in semiarid regions, a decrease in runoff retards erosion.

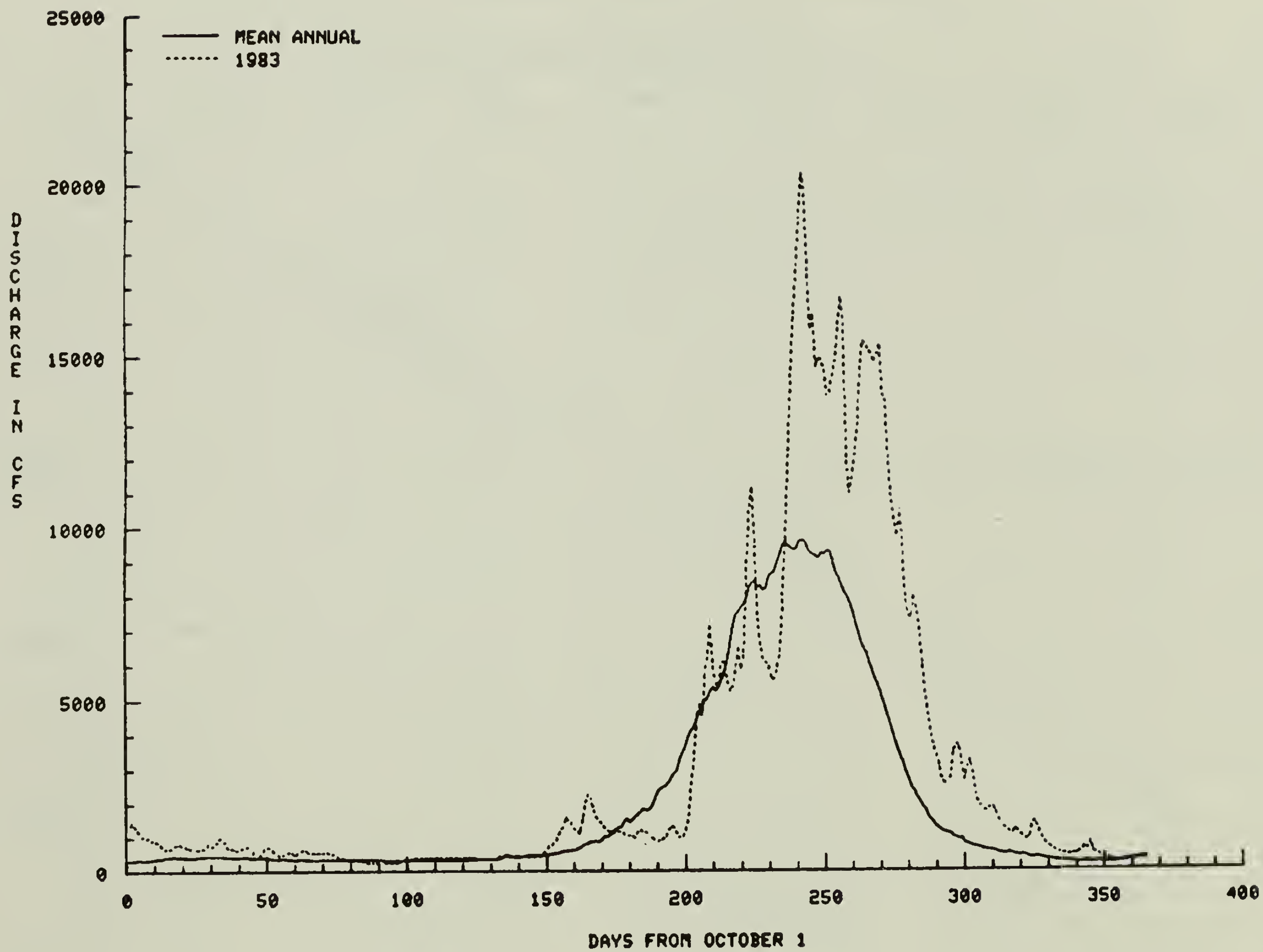
Instantaneous peak discharges are generally used to estimate discharge frequency. Since the flows from the two gaging stations are combined to determine the mean daily discharge at Deerlodge Park, the use of instantaneous peak discharges is inappropriate. Discharges of a specified return period are determined by the application of a theoretical probability distribution. Richards (1982) reports that the Gumbel Extreme Value distribution is a model which generates a linear function on a transformed probability scale. It is a two parameter model which seems to yield more representative values for the Yampa River than the log-Pearson type III model. The results of the Gumbel distribution and log-Pearson type III are shown in Table II. The Gumbel distribution is plotted in Figure 11. The 1983 peak discharge of 20,300 cfs has a return period of approximately 13 years based on the Gumbel analysis and over 20 years based on the log-Pearson type III. Four discharges in 62 years have exceeded 20,000 cfs which is a return period of about 15 years. The maximum recorded peak discharge was 21,750 cfs in 1974 (see Table III). The one hundred year event is about 27,000 (Gumbel) and 22,000 cfs (Pearson).

The 1983 Yampa River hydrograph in the Monument had the fourth highest peak discharge and the third largest annual volume in the 62 years of historical record. These values are 6.7% and 22.6% smaller than the maximum historical discharge and volume respectively.



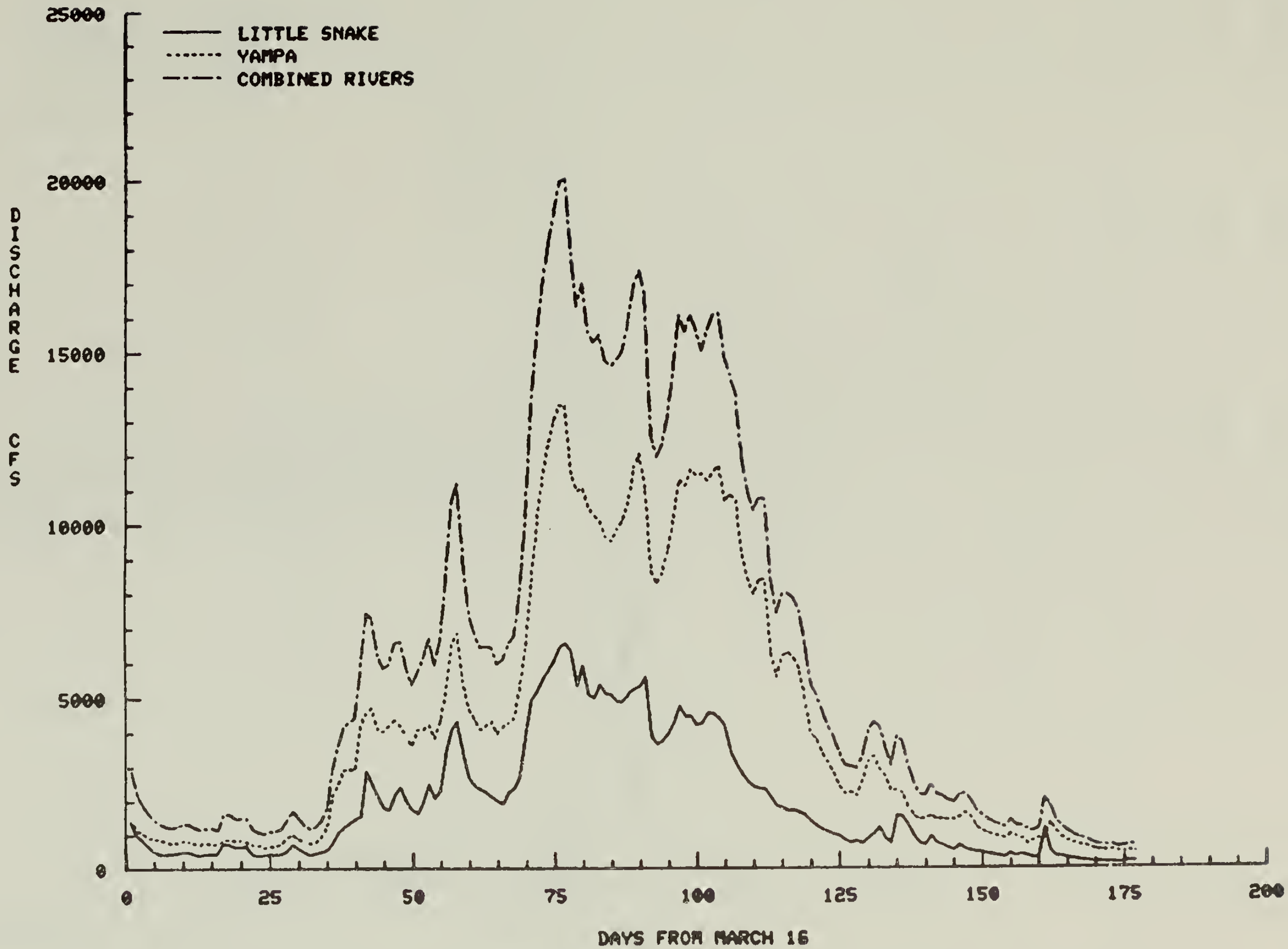
COMPARISON OF MEASURED AND USGS DISCHARGE

Figure 6



YAMPA RIVER DISCHARGE - DEERLODGE PARK, 1983 & MEAN

Figure 7



YAMPA - LITTLE SNAKE RIVERS HYDROGRAPHS 1983

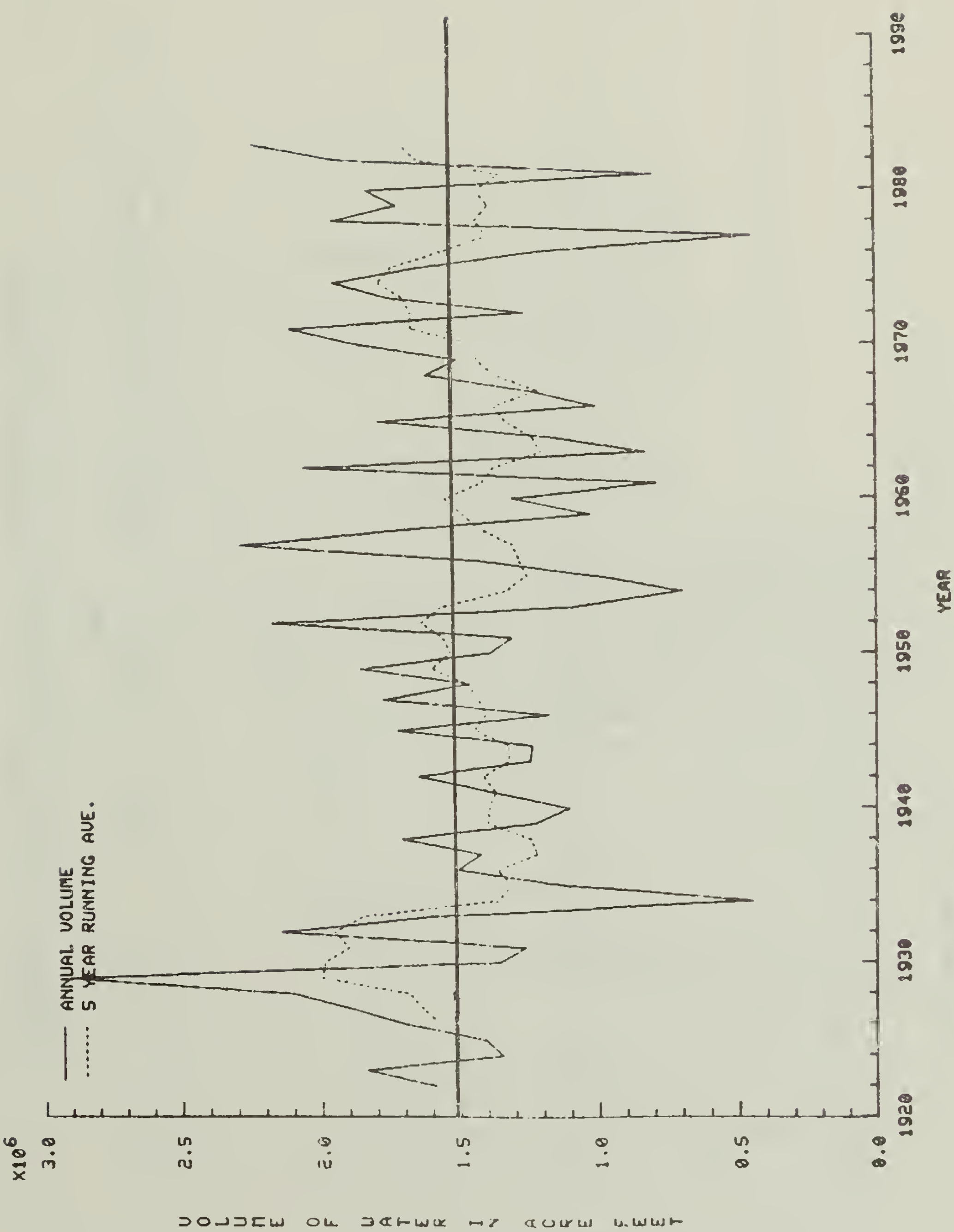
Figure 8

Table I. Historical Flow at Deerlodge Park

Period	Mean Annual Discharge (cfs)	Mean Annual Flow (acre-feet)	Base Flow Sept 1 - Feb 28 (cfs)	Mean Annual Peak (cfs)
1922-38	2,221	1,609,100	435	11,391 (May 28)
1941-83	2,048	1,483,700	367	9,597 (May 30)
1922-83	2,082	1,508,400	384	9,892 (May 29)

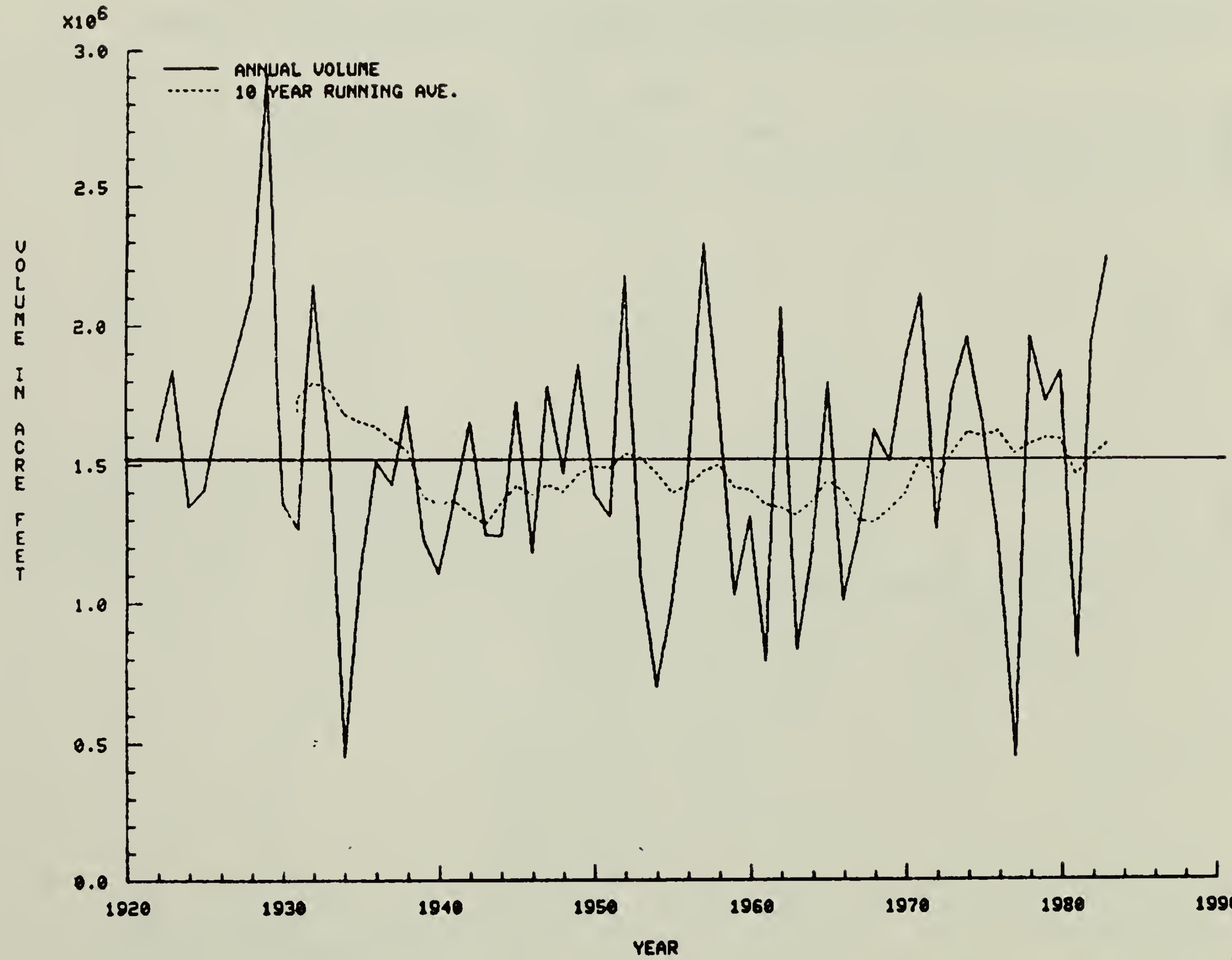
Table II. Flood Frequency Analysis

Return Period (years)	Discharge (cfs)	
	Gumbel	log-Pearson type III
1.01	12,000	
1.05	12,120	
1.10	12,270	
1.25	12,690	
1.5	13,280	
2	14,220	14,070
5	17,200	17,710
10	19,460	19,270
20	21,720	20,170
25	22,450	20,630
50	24,700	21,340
100	26,960	21,850
200	29,220	22,240
500	32,200	
1000	34,460	23,240



YAMPA RIVER ANNUAL DISCHARGE VOLUMES AND 5 YEAR RUNNING AVE.

Figure 9



ANNUAL VOLUME AND TEN YEAR RUNNING AVERAGE

Figure 10

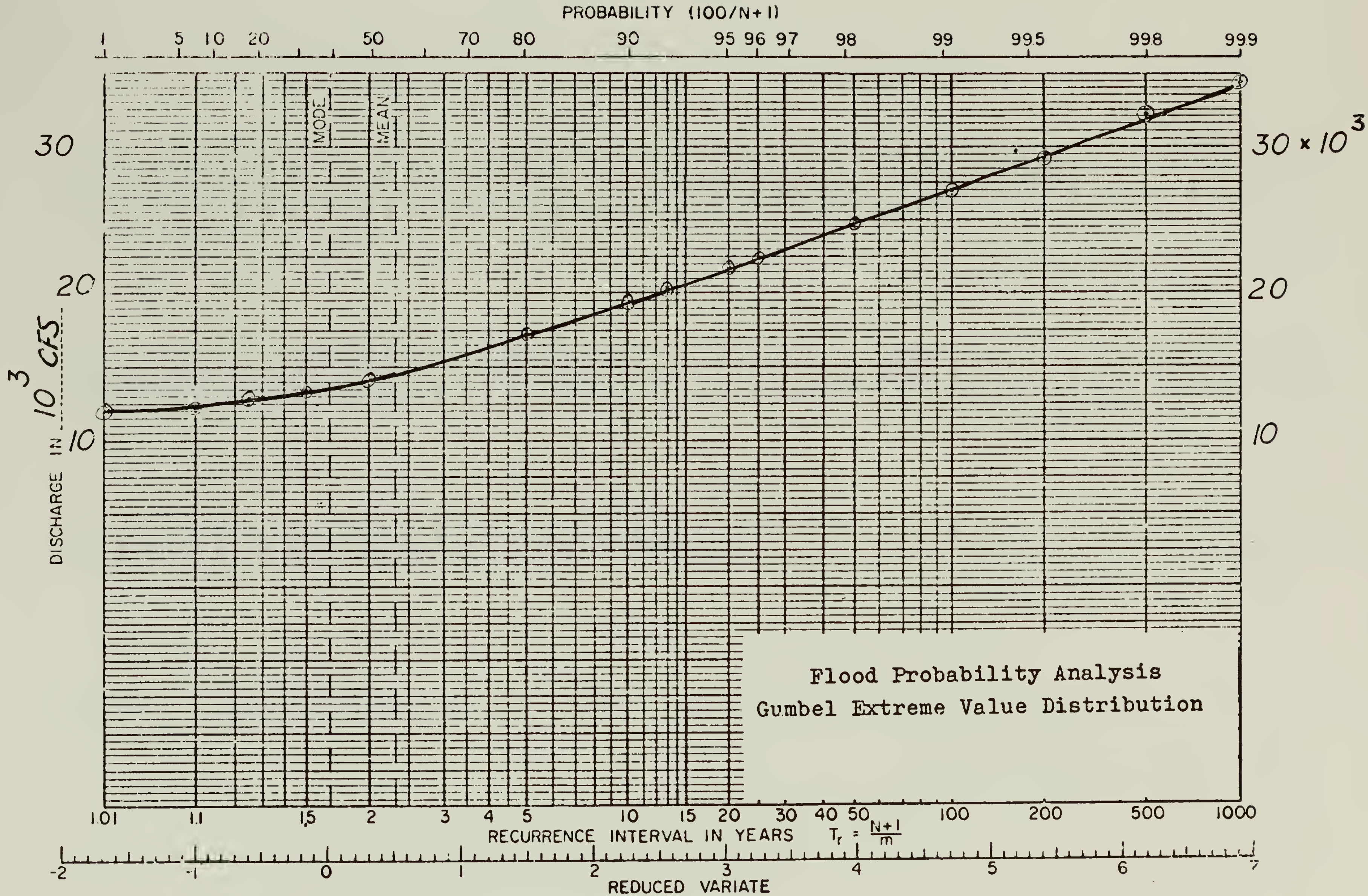

PROBABILITY (100/N+1)
1 5 10 20 50 70 80 90 95 96 97 98 99 99.5 99.8 99.9
MODE
MEAN
DISCHARGE IN 10^3 CFS
30
20
10
30×10^3
Flood Probability Analysis
Gumbel Extreme Value Distribution
1.01 1.1 1.5 2 3 4 5 10 15 20 30 40 50 100 200 500 1000
RECURRENCE INTERVAL IN YEARS $T_r = \frac{N+1}{m}$
-2 -1 0 1 2 3 4 5 6 7
REDUCED VARIATE

Figure 11

Table III. Historical Peak Flow and Annual Volume

Rank	Year	Flow (cfs)	Volume (acre-feet)
1	1974	21750	1956125
2	1929	21680	2902553
3	1957	20520	2289240
4	1983	20300	2246512
5	1952	19920	2175005
6	1928	18990	2106429
7	1938	18950	1708732
8	1932	18800	2144967
9	1970	18420	1869818
10	1979	18120	1727802
11	1971	17900	2112790
12	1973	17270	1751740
13	1947	17080	1777476
14	1980	17030	1835731
15	1958	16740	1693288
16	1927	16730	1887604
17	1943	16330	1244955
18	1975	16320	1639329
19	1926	16160	1691386
20	1922	16150	1584567
21	1978	16150	1958202
22	1962	15790	2060738
23	1945	15750	1722819
24	1968	15750	1622582
25	1923	15500	1838252
26	1965	15440	1793325
27	1941	15350	1384672
28	1933	15090	1599209
29	1982	15070	1943124
30	1942	14920	1649526
31	1948	14910	1466055
32	1937	14740	1426433
33	1936	14490	1508971
34	1964	14210	1184427
35	1944	14120	1241415
36	1949	13350	1857943
37	1956	12920	1443543
38	1953	12440	1097929
39	1950	12300	1393951
40	1967	12030	1253888
41	1935	11970	1120021
42	1940	11950	1106580
43	1951	11540	1310703
44	1972	11090	1266828
45	1969	10980	1508031
46	1939	10850	1233386
47	1976	10790	1207034
48	1960	10600	1310152
49	1924	10570	1347465
50	1930	10080	1359346

Table III. Continued.

Rank	Year	Flow (cfs)	Volume (acre-feet)
51	1946	9830	1179419
52	1931	8890	1265287
53	1955	8850	1005751
54	1981	8650	802459
55	1925	8590	1408446
56	1966	8330	1008993
57	1963	8250	833860
58	1959	8220	1029978
59	1961	7680	792112
60	1954	6780	700438
61	1934	4402	454095
62	1977	3821	448427

Effective Discharge and Bankfull Discharge

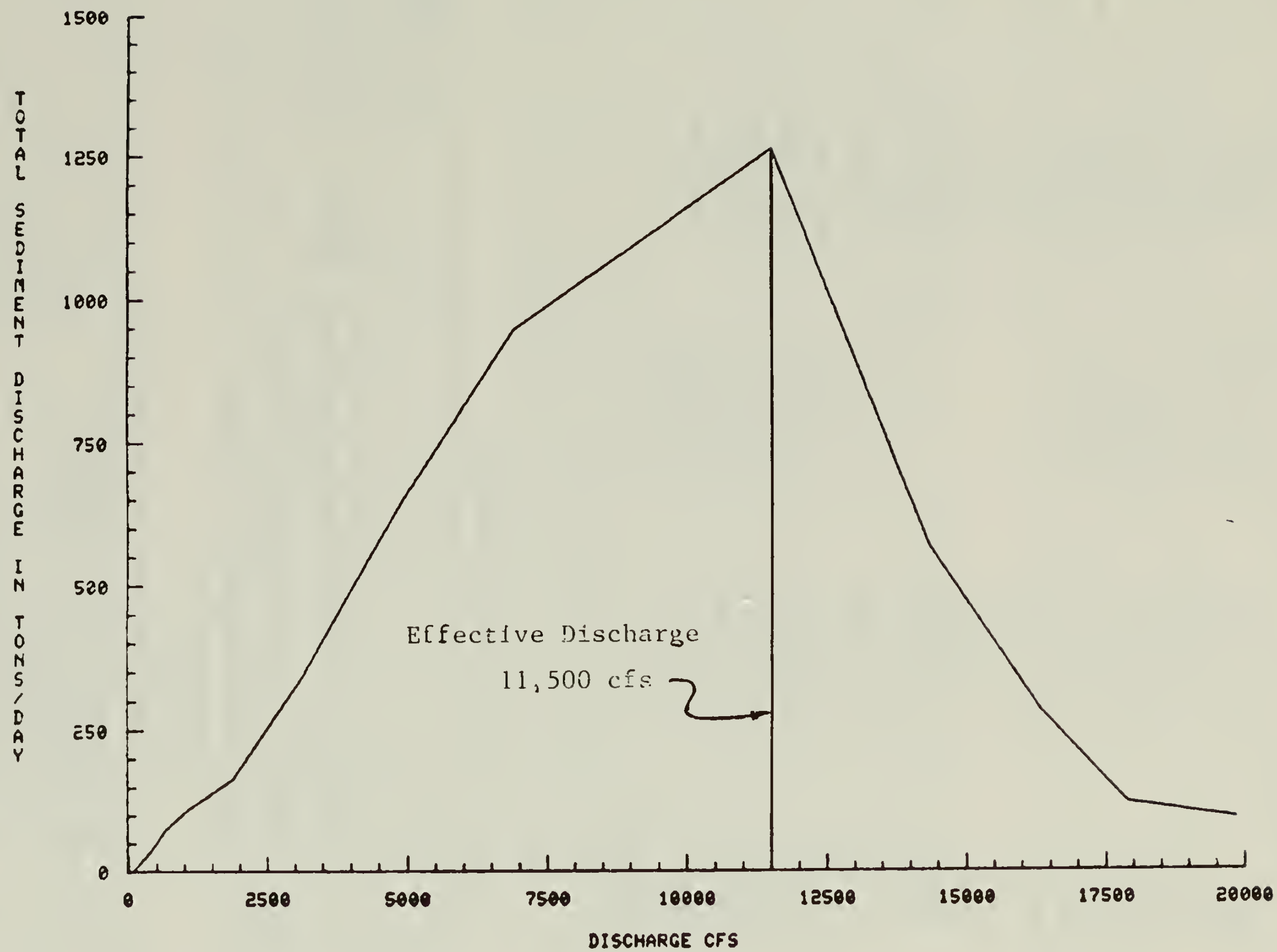
Effective discharge is the flow that transports the most sediment over a long period of time. It is the product of the magnitude of the sediment transported by a given discharge and the frequency of occurrence of that discharge. The effective discharge is approximately 11,500 cfs as shown in Figure 12. The return period for this discharge is about 1.5 years. From the stage-discharge relationship and survey measurements at Mathers Hole, the bankfull discharge was calculated to be approximately 21,500 cfs, which has return period of about 20 years.

Bankfull discharge is usually afforded the status of a "dominant" discharge event which controls channel morphology. It is responsible for creating the channel morphological characteristics, changing width/depth ratios, forming or destroying bars and islands, and changing bends and meanders. For alluvial streams this is often an intermediate magnitude flow with a return period of 1.5-2.0 years (Rosgen, 1982). Such a discharge is sufficiently frequent to be an effective channel-forming event. Large floods are too infrequent to control channel morphology. The Yampa River, however, is not alluvial stream in the canyon, but an incised river with an armored bed whose channel adjustment flows are limited to infrequent events.

In the cobble reach, the Yampa River has incised a channel below the floodplain terrace. This incision has reduced the frequency of overbank flooding, and the bankfull discharge has a return period of 20 years. Bankfull discharge has also been determined to be the discharge which moves the median size bed material. This evidence supports the conclusion that the bankfull discharge is the channel forming flow. Channel morphology in the canyon is not adjusted with every seasonal variation in discharge. The dynamic nature of the cobble substrate reach is maintained by bankfull discharge which reforms the bar shape and orientation and reorders the substrate size distribution in local areas. Bedload transport of the large cobble substrate occurs with discharges in excess of bankfull discharge. The channel width will adjust to form the most efficient section for the cobble bedload transport. Rare floods, therefore, have the most significant effect on channel morphology in the Yampa Canyon.

Sediment Transport

There is no corresponding period of record for daily sediment discharge at the Maybell and Lilly gaging stations. Five years of daily sediment discharge measurements were collected by the USGS for water years 1960 through 1964 for the Little Snake and 1952 through 1958, 1976, and 1978 through 1982 for the Yampa, 13 years of record (see Table IV). For these short records the mean annual suspended sediment load was 1,341,300 tons for the Little Snake and 407,200 tons for the Yampa; total of approximately 1,748,600 tons/year of suspended sediment delivered to the Monument. The mean annual flow during these years was 1,418,400 or 4.4% less than normal for the 1941-83 period. During this period, however, one extreme year of sediment discharge occurred for the Little Snake. If 4 days in 1962 (1,156,000 tons) are excluded from the



EFFECTIVE DISCHARGE

Figure 12

Table IV. Historical Sediment Data

Water Year	Yampa, Maybell Discharge (acre-feet)	Yampa, Maybell Sediment Load (tons/year)	Little Snake, Lilly Annual Discharge (acre-feet)	Little Snake, Lilly Sediment Load (tons/year)
1952	1,447,177	547,740	727,828	
1953	829,208	247,886	268,721	
1954	522,182	125,025	178,256	
1955	772,587	401,893	233,164	
1956	1,033,298	397,647	410,900	
1957	1,781,336	607,486	507,000	
1958	882,840	511,717	425,000	
1960	1,010,000		300,301	931,650
1961	629,300		162,779	438,142
1962	1,492,000		569,128	3,156,957
1963	630,200		203,601	958,285
1964	865,200		318,014	1,221,563
1976	826,300	246,508	382,400	
1978	731,628	500,450	507,000	
1979	660,582	232,540	417,500	
1980	645,121	651,042	557,400	
1981	279,388	187,247	248,300	
1982	692,174	618,903	570,100	
Average		407,237		1,341,319

Table V. Load Duration Analysis

		Annual Load (million tons/year)
1.	Historical combined gaging stations, Maybell and Lilly	1.21
2.	Same as #1 using seasonal analysis	1.20
3.	USGS, measurements at Deerlodge	
	a. Suspended Load	1.94
	b. Sand Load	0.79
	c. Total Load (including bedload)	2.04
4.	Mathers Hole Data (1983)	
	a. Fine Load (<0.0625 mm)	1.22
	b. Sand Load	0.97
	c. Helley-Smith Load	0.0062
	d. Unmeasured Sands	0.038
	e. Suspended Load	2.13
	f. Total Load	2.16

analysis, the average annual suspended sediment load from the Little Snake is 1,110,100 tons per year and the mean annual suspended sediment load for the combined rivers is only 1,517,300 tons per year.

Compared to 1982, the 1983 field season at Mathers Hole incorporated improved data collection techniques, a greatly expanded sampling program, and collection of samples on both the rising and recessional limb. The '82 and '83 data are combined where appropriate in the analysis of sediment transport, but the 1983 data is generally used in obtaining sediment discharge versus water discharge regression relationships. These sediment regressions are presented in Table VI. The coefficient of determination (r^2) is higher for the recessional limb than the rising limb and the correlation between the sediment load and water discharge is excellent (see Figures 13 through 18). The Mathers Hole and Deerlodge suspended sediment rating curves are nearly identical (Figure 14). Excellent correlation was found with USGS measured suspended load at Deerlodge Park and is shown in Table V and Figures 13 and 14.

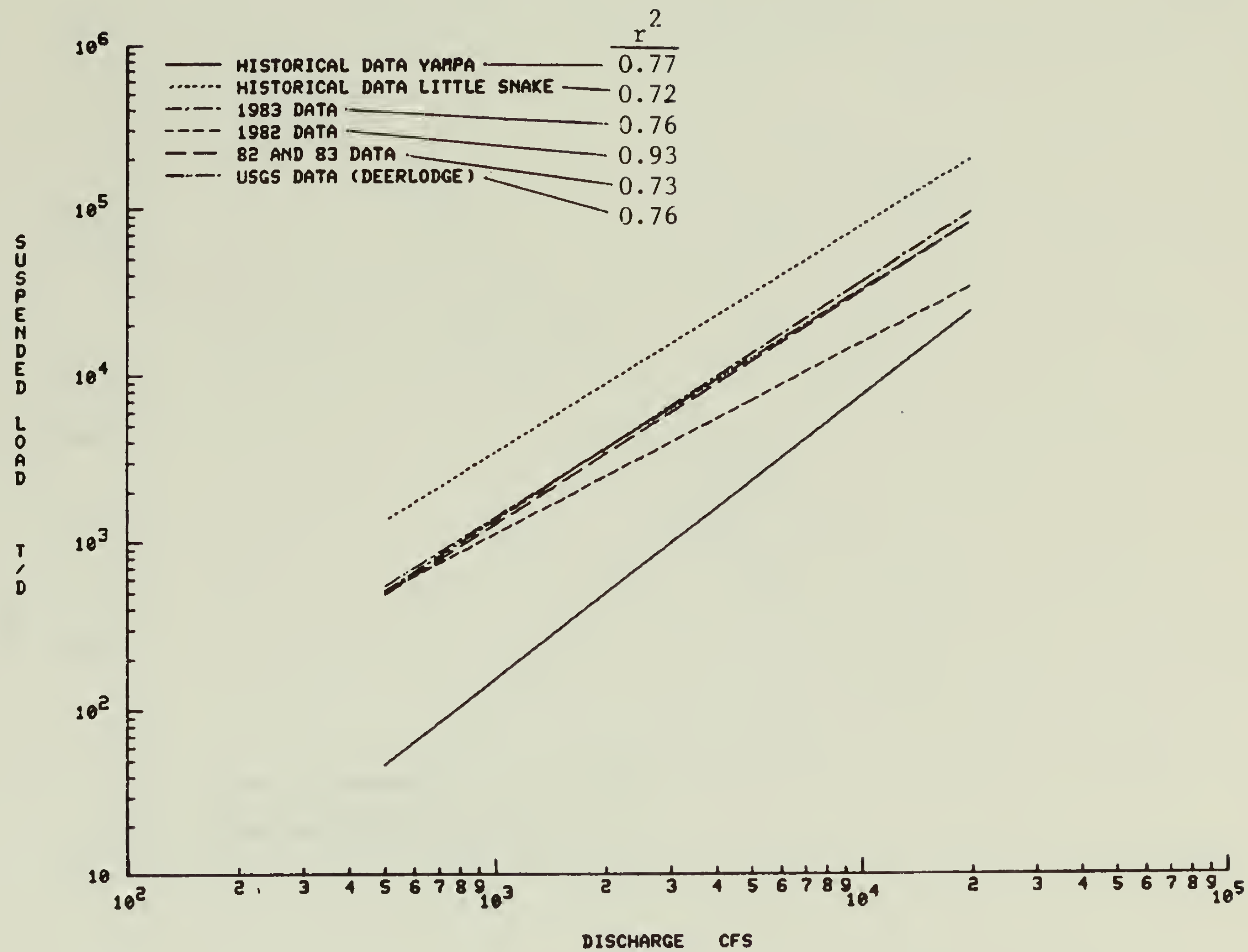
With these regressions and a flow-duration curve, and a load-duration analysis was performed on Mathers Hole data (Table V). The total suspended load using all the data from 1982 and 1983 is 1.91 million tons per year and alone, the 1983 suspended load is 2.13 millions tons per year. Applying the load-duration analysis to the historical gaging station data, the average suspended load is calculated to be 1.20 million tons/year, significantly less than the average annual measured suspended load at the gaging stations and that calculated from the Mathers Hole data. Andrews (1980) reported the average sediment yield for the Yampa Basin at 2.0 million tons per year. The load-duration analysis when applied with log regression relationships of sediment and water discharge will underpredict the annual sediment load. The best estimate of an average annual sediment load is 1.5-1.6 million tons/year from the gaging station records. Last year's sediment load represents a substantial higher sediment yield for the basin.

The Helley-Smith sampler when combined with D-74 depth integrating suspended sampler is sampling, in theory, the entire flow zone of river. Only the sand sizes less than 0.25 mm which slip through Helley-Smith collection bag are missed in the sampling process. This sand fraction is referred to as the unmeasured sand load. The modified Einstein method for predicting total sediment load in the stream was applied to predict the unmeasured sand load. The results are presented in Tables V and VI. The unmeasured sand load was estimated to be 2% of the annual total load.

Nine sets of data were collected at Mathers Hole in 1982 and forty-three sample sets in 1983. A statistical comparison was undertaken to determine if any substantial differences in the measured sediment data could be discerned. The data was divided into two categories involving the rising and recessional limbs of the hydrograph. The variables, total suspended concentration, suspended load, fine material load, and Helley-Smith load were tested. Assuming independent random samples of two normal populations with unknown means and variances, the t-test was used to accept or reject the hypothesis that there was no significant difference between the populations at the 5% significance level.

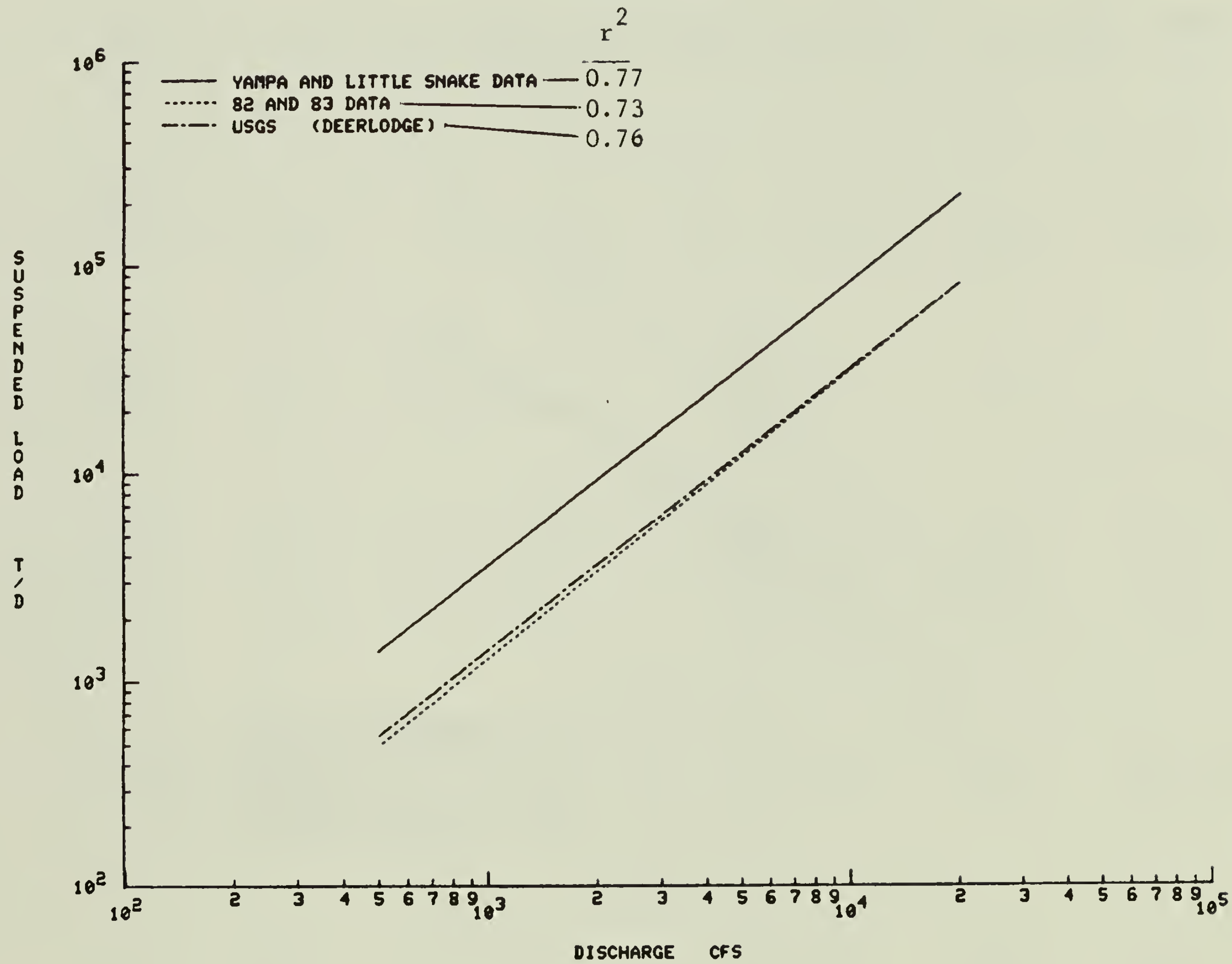
Table VI. Sediment Regression Relationships $Q_s = a\,Q^b$ (tons/day)

Description	No. of Points	Coefficient a	Exponent b	Coefficient of Determination r^2
Suspended Fines (<.0625 mm)				
Rising Limb, 1983	26	2.96×10^{-2}	1.497	0.84
Recessional Limb, 1983	14	4.57×10^{-3}	1.608	0.92
All Points, 1983	40	4.70×10^{-2}	1.408	0.80
Suspended Sand (>.0625 mm)				
Rising Limb, 1983	26	4.13×10^{-11}	3.742	0.94
Recessional Limb, 1983	14	4.69×10^{-10}	3.288	0.98
All Points, 1983	40	1.20×10^{-9}	3.283	0.91
Helley-Smith (unmeasured load)				
Rising Limb, 1983	29	2.91×10^{-5}	1.588	0.68
Recessional Limb, 1983	13	3.10×10^{-8}	2.436	0.80
All Points, 1983	42	1.07×10^{-6}	2.005	0.75
1982 Data	7	3.47×10^{-6}	2.041	0.85
All Points, 1982 & 1983	50	1.31×10^{-6}	2.012	0.70
Recessional Limb, 1982 & 1983	21	5.79×10^{-7}	2.167	0.71
Total Suspended Load				
Rising Limb, 1983	29	1.68×10^{-1}	1.352	0.75
Recessional Limb, 1983	14	6.54×10^{-4}	1.885	0.93
All Points, 1983	43	7.59×10^{-2}	1.417	0.76
1982 Data	7	9.57×10^{-5}	2.079	0.93
All Points, 1982 & 1983	52	8.55×10^{-2}	1.391	0.73
Recessional Limb, 1982 & 1983	22	1.48×10^{-3}	1.795	0.87
Unmeasured Sands				
Rising Limb, 1983	26	8.33×10^{-10}	3.074	0.93
Recessional Limb, 1983	14	2.54×10^{-8}	2.519	0.98
All Points, 1983	40	3.211×10^{-8}	2.585	0.88
Total Sediment Load				
Rising Limb, 1983	29	1.66×10^{-1}	1.354	0.75
Recessional Limb, 1983	14	6.51×10^{-4}	1.887	0.94
All Points, 1983	43	7.42×10^{-2}	1.421	0.76



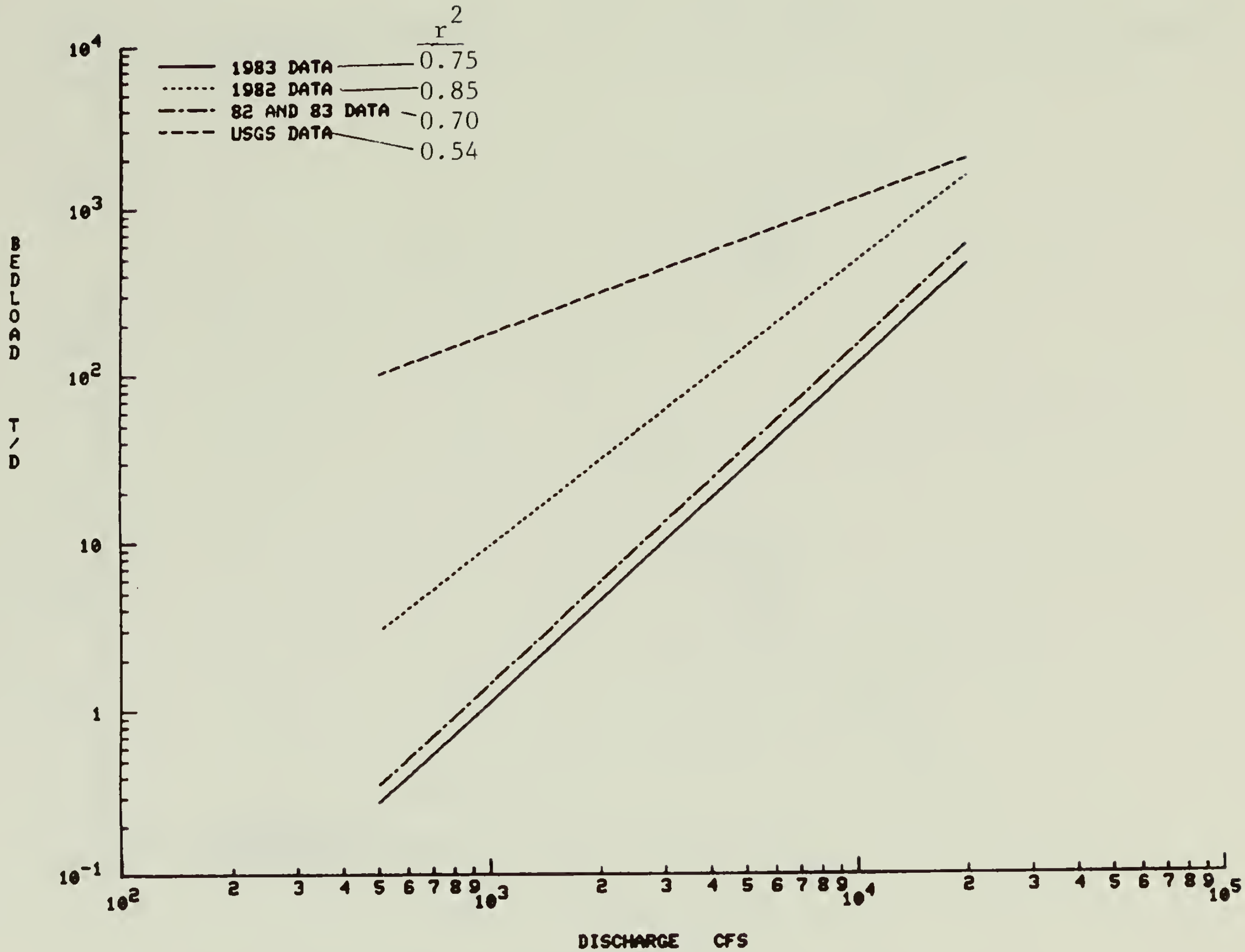
SUSPENDED LOAD REGRESSION PLOTS

Figure 13



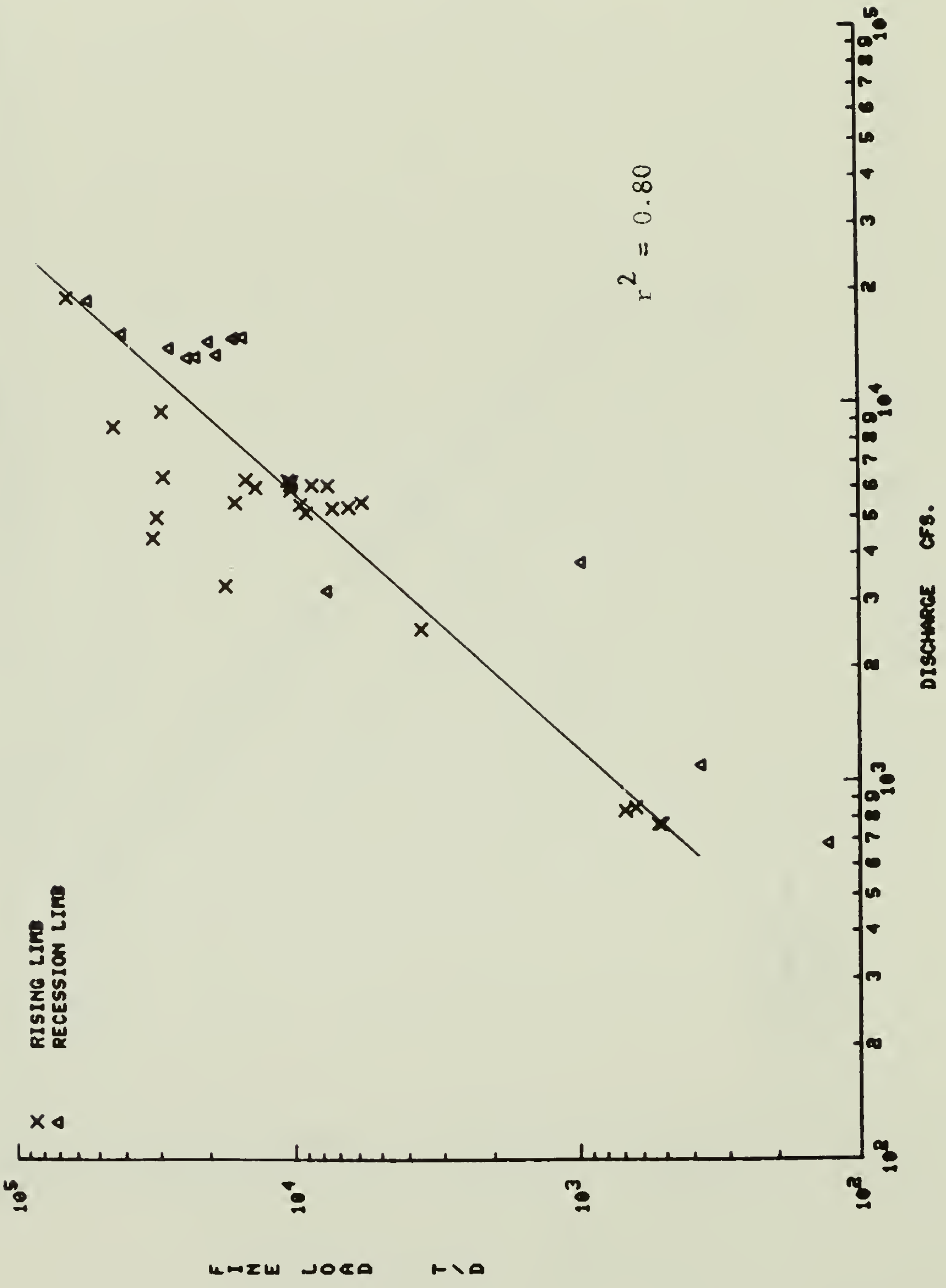
SUSPENDED LOAD REGRESSION PLOTS

Figure 14



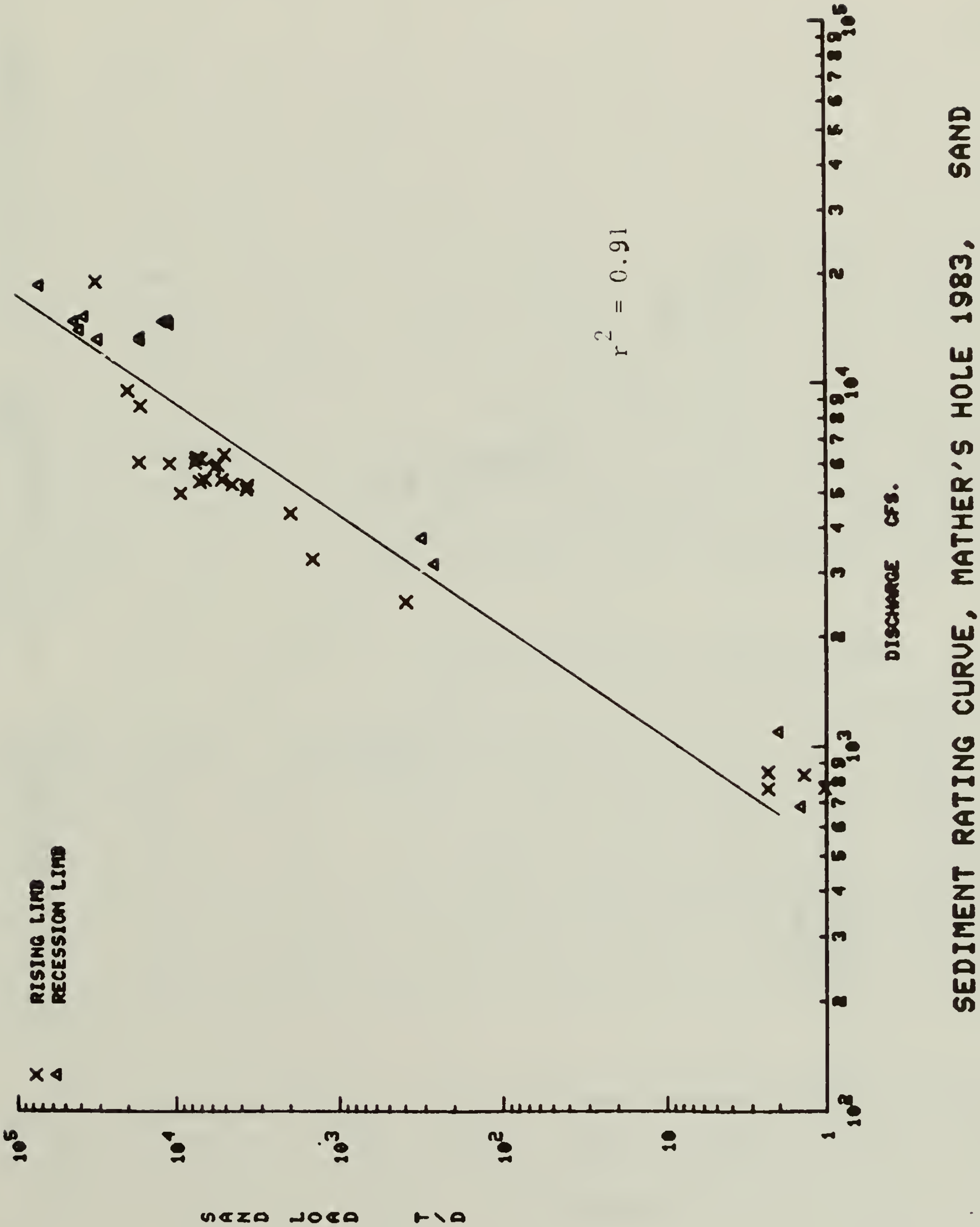
BEDLOAD REGRESSION PLOTS

Figure 15



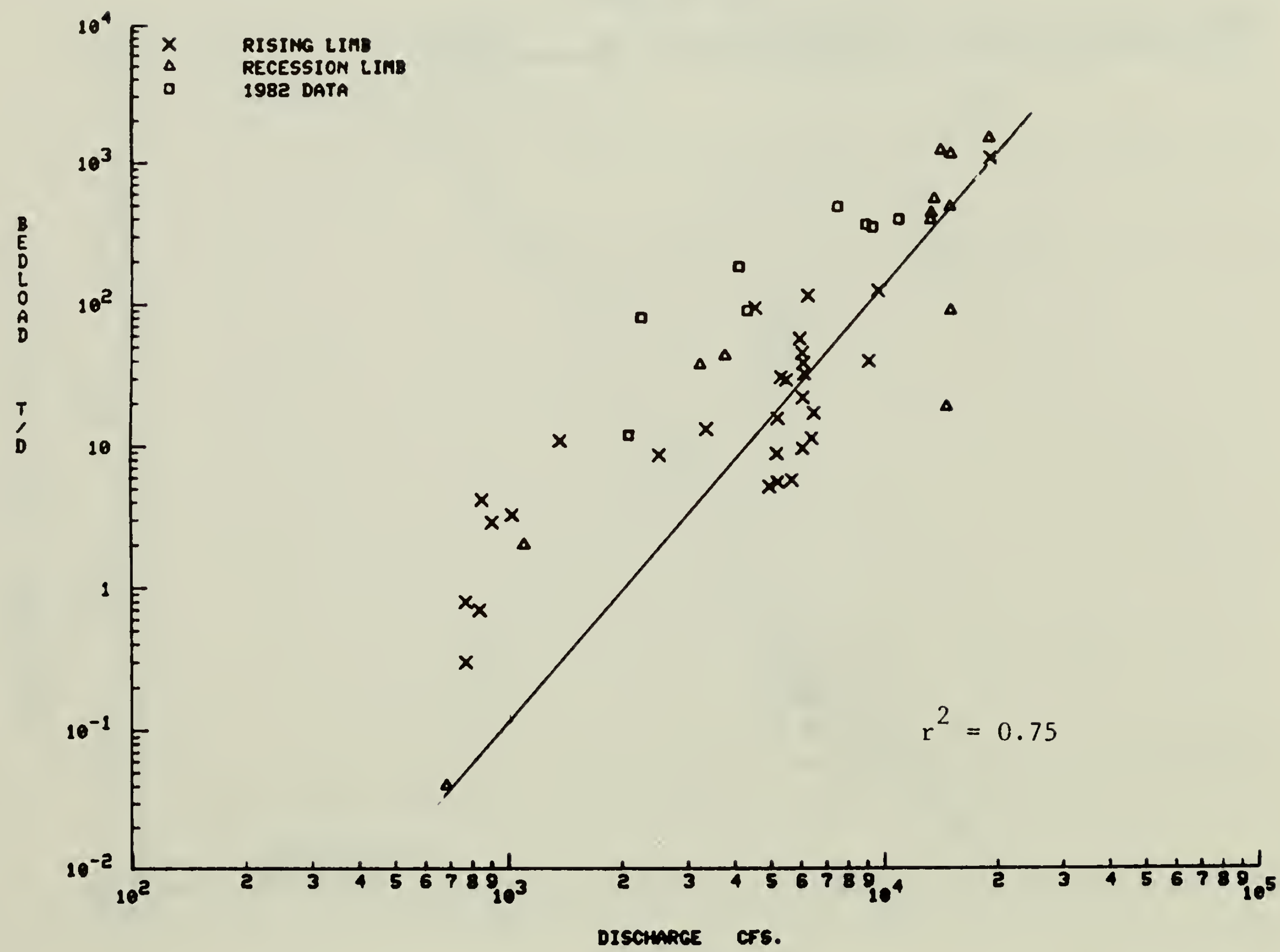
SEDIMENT RATING CURVE, MATHER'S HOLE 1983, FINES

Figure 16



RISING LIMB
RECESSION LIMB
$r^2 = 0.91$
SAND LOAD T/D
DISCHARGE CFS.
SEDIMENT RATING CURVE, MATHER'S HOLE 1983, SAND

Figure 17



BEDLOAD RATING CURVE, MATHER'S HOLE 1983

Figure 18

The statistic test was carried out using the Minitab statistical regression computing system. The results show that there was a significant difference between the rising and recessional suspended sand load, the rising and recessional Helley-Smith load, and the rising and recessional fine material concentration for 1983. Further, there were also significant differences between 1982 and 1983 recessional total suspended loads and between the 1982 and 1983 total suspended load and concentration for all the measured samples (see Table VII).

Substantially more sediment was transported through the Yampa Canyon in 1983 than in 1982. If discharge was the sole factor responsible for the increase in sediment loads, then essentially no differences would be detected in the sediment rating curves. The results show that the Helley-Smith load is the same from year to year, but variation occurs between the rising and falling limbs of the hydrograph. This may be explained by the coarse sand bedload travel time from the source area at Deerlodge to the Mathers Hole sampling site. The concentration and fine material load are relatively less for a given discharge on the falling limb than on the rising limb indicating a reduction of the supply of sizes less than 0.0625 mm. The difference in total suspended concentrations between 1982 and 1983 recessional limbs was not significant, but the water discharge accounted for a substantial difference in the total suspended load. Finally, the missing rising limb measurements in 1982 may account for the difference in total suspended concentration and load when compared with 1983 data. The foregoing analysis demonstrates the variability of the concentration and sediment load on a seasonal and annual basis. Since the sediment load in the river is supply limited, large differences should be expected from year to year.

Transported Sediment and Substrate Size Distributions

Throughout the Yampa Canyon the bed material size is observed as a function of slope; steeper sloped reaches having boulder and cobble size substrate and the milder sloped reaches, gravels and sands. The upstream twenty miles, which are very steep with an average slope between .0024 and .0035, have angular boulder substrate. The study reach between river mile 16.5 and 20.5 has an average slope of approximately .0013 and a riffle-pool sequence with substrate of predominately cobbles. The bed material from river mile 16.5 to the confluence with the Green River, excluding Warm Springs rapid, is comprised mostly of small to medium cobbles, gravels and some sand and has a slope ranging from .00079 to .0011 (Figure 2).

The surface substrate of the cobble bars varies from the upstream tip to the downstream tip of the bar. The substrate D_{50} is 100 mm for the upstream portion of the RM 16.5 cobble bar and 50 mm for the downstream portion. The combined upstream and downstream substrate samples is 70 mm (Figures 19-21). This corresponds well with the D_{50} size of 75 mm for the cobble substrate at Mathers Hole. The porosity of the cobbles is about 0.42. This is a typical value for natural grain noncohesive material (standard Ottawa sand ranges from 0.33 to 0.44). All of the cobble substrate material is locally derived from side canyon tributaries or mass wasting processes on the talus slopes and bedrock walls.

Table VII. Statistical Analysis of Sediment Discharge t-test of Variables with Unknown Means and Variances

Variable	Description	Sample Size	Variance Hypothesis*
Q_s	1983 rising vs. recessional	26,14	Rejected
Q_f	"	26,14	Accepted
Q_{st}	"	29,14	Accepted
Q_{hs}	"	29,13	Rejected
C_s	"	26,14	Accepted
C_f	"	26,14	Rejected
C_{st}	"	29,14	Accepted
Q_{st}	1982 vs. 1983 recessional	14,9	Rejected
Q_{hs}	"	8,13	Accepted
C_{st}	"	9,14	Accepted
Q_{st}	1982 vs. 1983 all data	9,43	Rejected
Q_{hs}	"	8,42	Accepted
C_{st}	"	9,43	Rejected

where: Q_s = suspended sand load

Q_f = suspended fine material load (<0.0625 mm)

Q_{st} = total suspended load

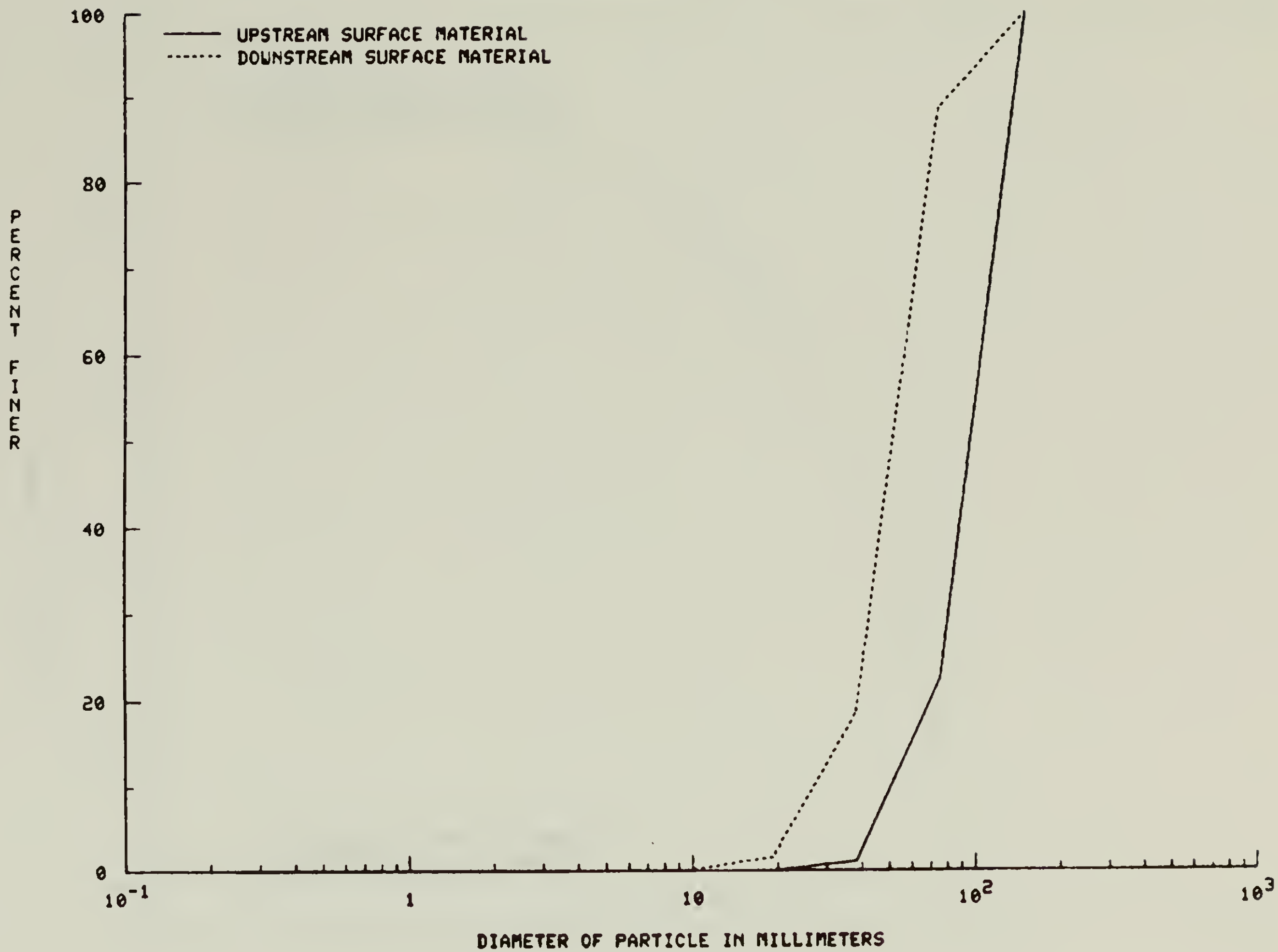
Q_{hs} = Helly-Smith load

C_s = concentration of sands

C_f = concentration of fine material

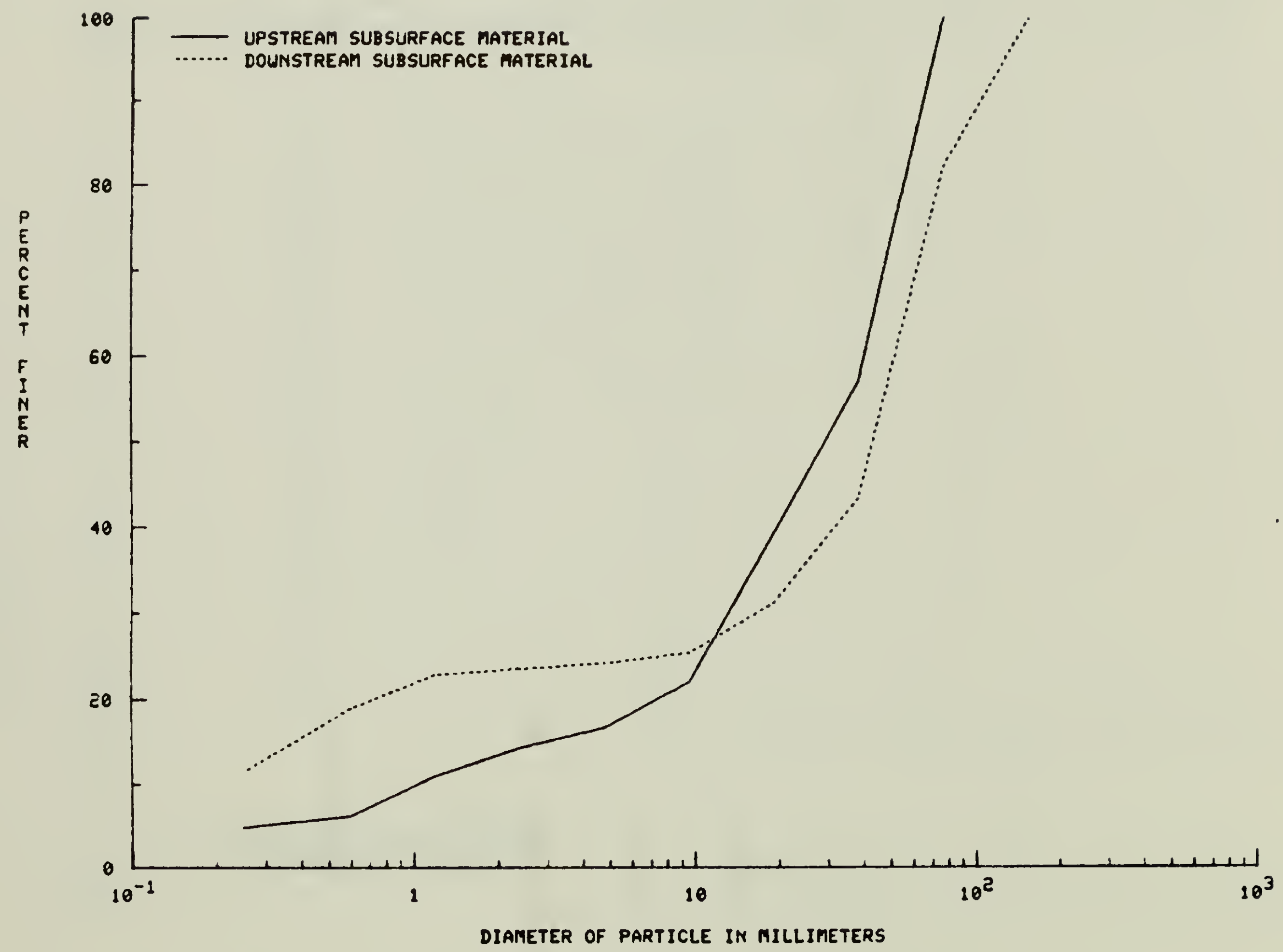
C_{st} = total suspended concentration

*Hypothesis: No significant difference between the populations at the 5% significance level using the t-test.



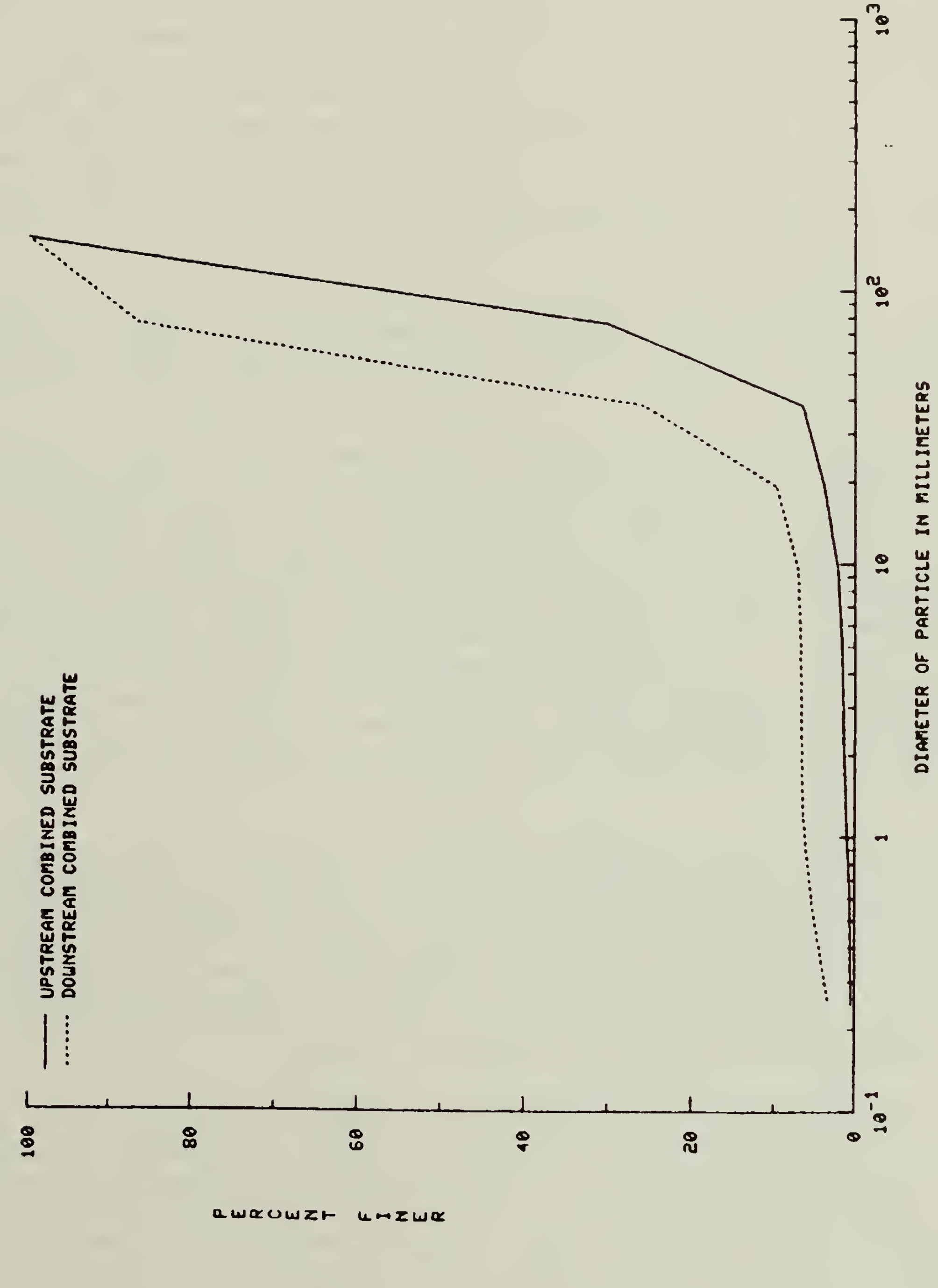
RIVER MILE 16.5 COBBLE BAR SURFACE SUBSTRATE

Figure 19



RIVER MILE 16.5 COBBLE BAR SUBSURFACE SUBSTRATE

Figure 20



RIVER MILE 16.5 COBBLE BAR COMBINED SURFACE AND SUBSURFACE SUBSTRATE

The wide range of grain sizes leads to two important features of bed heterogeneity, surface armoring and bimodal grain size distributions. Figure 21 reveals the armor nature of the surface bed material. Figure 20 shows a bimodal distribution in the subsurface substrate sizes. Transport modes depend on surface armoring and the availability of the finer sizes.

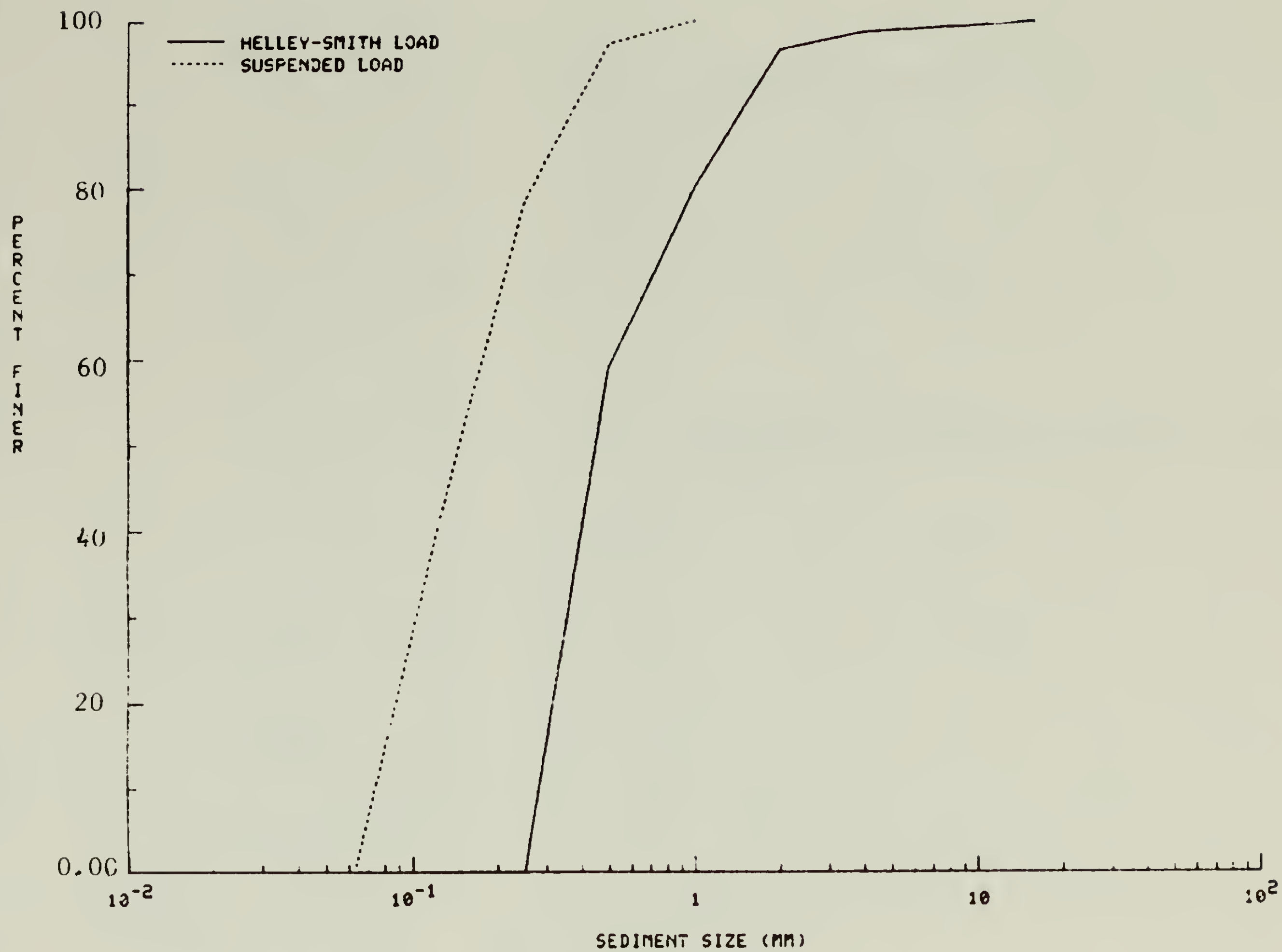
The Helley-Smith load is significantly coarser than the suspended sand load, but constitutes only 0.4% of the total load (Figure 22). Only the size fractions smaller than 1.0 mm were suspended high enough above the bed to be captured by the suspended sampler. The sediment particles greater than 1.0 mm (coarse sand) could be captured only by the Helley-Smith sampler and were not suspended higher than 3 inches above the bed. The median particle size captured in the sampler was 0.42. This is approximately one hundred-seventy times smaller the median bed material size indicating that all the transported sand is wash load. The Helley-Smith load median diameter is also seventy times smaller than the subsurface substrate.

The Helley-Smith sampler, from the peak flow (May 31) through June 24, collected gravels and cobbles moving on the bed. A total of 42 coarse gravels greater than 19 mm and five small cobbles were captured by the sampler. Most of the cobbles were disc-shaped.

Recent work by Andrews (1983) and Parker (1982) indicate that particles as large as the median diameter of the river bed substrate are entrained by discharges which equal or exceed the bankfull discharge. Entrainment of a given size particle has been shown to be a function of the bed material size distributions. Differential entrainment of the coarse bed fraction occurs in a relatively narrow range of shear stress (Andrews, 1983). From observations at Mathers Hole, the bedload consisted of relatively few large gravels and cobbles at the peak discharge, but included some of all particle sizes smaller than the median substrate size. General motion of the entire bed was not observed at Mathers Hole and changes in the cross section configuration could not be detected.

Using the entrainment criteria developed by Andrews (1983) for naturally sorted riverbed material, it has been determined that the critical dimensionless shear stress is approximately equal to 0.03 for the median substrate material (D_{50} = 75 mm). This is the same criteria used in last year's analysis referencing Parker's work (1982). The ratio of the threshold particle diameter to the median particle diameter of the subsurface bed material is the basis for determining the incipient motion criteria in Andrews' analysis.

Mobilization of the median bed material particle will ensue at approximately 21,500 cfs. All bed particles in the cobble reach, except the very largest, will be entrained at this discharge which corresponds to the bankfull discharge. Entrainment of the imbricated particles may require a larger critical shear stress. There is no evidence to support any prediction of large scale channel configuration change or erosion below bankfull discharge which is required to create a mobile-bed phenomenon. Evidence shows that even in a 'mobile bed' of coarse particles, movement is limited to short leaps and hops, the bed load at any instant still be relatively small (Butler, 1977).



TRANSPORTED SEDIMENT SIZE DISTRIBUTION

Figure 22

Sediment Deposition in the Canyon Riparian Zone

Twenty-one cross sections were established early in the spring of 1983 and were monitored later in the fall to discern any and all changes that had occurred as result of general degradation or aggradation. The results are reported as an average change in the cross section per foot of active width of the channel during peak flow in Table VIII. Of the 21 cross sections, 13 aggraded and 8 degraded. The net effect on the canyon was aggradation with an average of 0.32 feet of deposition per foot of width of channel per cross section. Of the five cross sections established in pools above riffles or rapids in the steep reach of river upstream of Big Joe rapid, three cross sections aggraded, two degraded. Only the cross section at Tepee displayed a surprisingly large net loss of sand. The total change in the steep reach represented by these five cross sections is net degradation. In the cobble reach from river mile 16.5 to 20.5, three cross sections aggraded, two were scoured. The overall effective change on this reach was negligible. From river mile 10 through 16.5 (from Warm Springs Lake to the spawning site), characterized as a gravel-small cobble reach with a mild slope and a riffle-pool sequence three cross sections degraded while six aggraded. The net change in this reach was apparent deposition. In the sand bed reach of Warm Srings Lake one cross section aggraded substantially while the other degraded by an equivalent amount. The upstream cross section, which is the upstream extent of the backwater created by Warm Springs rapid, aggraded. The cross section one mile upstream of the rapid scoured. The single side canyon cross section at Portal Canyon was completely blocked by sand deposition to a height of six feet. A large portion of this sand had already been removed by a flushing event of the side canyon by the end of August. Most of sand deposition or scour was confined to a relatively small portion of the cross section with the exception of the last two which were predominately sand bed. The areas of significant deposition occurred where large eddies formed during peak flow.

The greatest potential for sediment deposition occurs in the lower one-third of the canyon, specifically in Warm Springs Lake, the pool above Warm Springs rapid. The cobble substrate reach retained little sand deposition after the 1983 runoff season, a year of high sediment discharge. During 1983 enough sand size sediment (59% of total load) entered the Yampa Canyon to fill a 300 foot channel, one foot deep, for over fifteen miles. The cross sections in first third of the canyon had a net loss of sediment, due in large part to scour at the pool above Teepee Rapid. The middle third of the canyon experienced no significant change in the existing channel. The lower one third of the Yampa River displayed a net increase in sand storage. Although each area sensitive to sand deposition throughout the canyon was not monitored, enough cross sections were surveyed to discern the general trend of deposition.

The transition between the riparian and upland vegetation zone was discernable at fourteen of the twenty-one canyon cross sections. Various riparian species were identified to mark the transition including, box elders, cottonwoods and squawbush. Juniper, cactus and grasses in the upland vegetation zone were also utilized in the seeking

Table VIII. Canyon Cross-Section Aggradation/Degradation Analysis

Cross Section	Width (feet)	Average of Aggradation/Degradation (feet/foot of width)
1	326	0.60
2	301	-1.72
3	347	0.21
4	190	-0.22
5	317	0.41
6	577	0.43
7	510	0.35
8	177	-0.60
9	239	-1.01
10	472	0.60
11	166	0.73
12	204	-0.71
13	220	0.67
14	253	-0.37
15	342	0.66
16	612	1.03
17	450	-0.12
18	282	0.60
19	280	1.57
20	251	1.27
21	290	-1.26
POR	54	2.22

The average change for all cross sections is 0.32 feet per foot of width per cross section.

the highest elevation of the riparian zone. This transition line was interpreted as the highest recent water surface elevation. A comparison between the demarcation line of the two zones and the 1983 high water elevation was surveyed in the field. In only three of fourteen surveys, the 1983 high water surface was higher than the riparian line. The 1983 surveys ranged from two foot below to one and a half feet above the riparian zone upper limit.

On the average the highest point of the riparian zone was approximately one half foot above the 1983 high water elevation. This close correspondence between the high flow last season and the riparian zone limit implies the riparian zone is inundated by peak flows with a return period of approximately seventeen years or equal to that of the bankfull discharge.

A reduction in the magnitude or frequency of flows inundating the riparian zone will result in the encroachment of riparian-vegetation into the channel area. This invasion would result in a loss of flood flow carrying capacity. The active channel is maintained by the peak flows on an annual basis. Bankfull discharge removes any vegetative invasion in riparian zone.

Physical Model Study

A physical model of the cobble substrate at river mile 16.5 was constructed in the eight foot flume at the CSU Engineering Research Center hydraulic laboratory to study the physical processes and measurement of sand transport over cobble substrate. A detailed description of the model investigation is presented in Appendix A. A discussion of the results follows.

The hydraulic and cobble substrate conditions of the channel at River Mile 16.5 were modeled on a one to one model to prototype basis (Photo 2). Three separate tests were performed. The purpose of the first test was to calibrate the sampling efficiency of the Helley-Smith bedload sampler on a cobble bed for a range of hydraulic conditions less than those required for incipient motion of the cobbles. The efficiency of the Helley-Smith was calibrated for hydraulic conditions over a sand bed in the second test. The third test consisted of an investigaton of sand scouring processes in cobble substrate. The data collected during these tests included water discharge, depth, mean velocity, velocity profiles, water surface slope, flume bed slope, Helley-Smith sediment load and total sediment load.

From the calibration tests of the Helley-Smith sampler, the following results are reported:

1) The Helley-Smith sampler will underpredict the sand bedload transport over a uniform cobble bed.

2) The sampler overpredicts for a sand bed with large transport rates.

3) Diversity of substrate improves the collection efficiency of the sampler.

Photo 2. Simulated Cobble Bed, Physical Model Study

The Helley-Smith sampler is sensitive to local hydraulic conditions on the bed. If the cobbles protrude above the sand bed level, sand will pass under the sampler nozzle resting on the top of cobbles (Photo 3).

Numerous observations were made on the phenomena of sand transport over and sand scour from a cobble bed. This information is important to understanding the processes required to sustain a cobble bed relatively free of sand over a range of hydraulic conditions. Sand moves as bedload through the cobble bed material in a series of interrupted waves and strings. As expected the sand rolled and saltated in and around the cobbles, scouring upstream of a cobble and being deposited in the wake of the cobble.

The sand bed was nearly level throughout the flume at a depth of one half to one cobble diameter below the average cobble bed height. When a small sand wave progressed through the test section, the sand bed was approximately the same level as the average cobble height. When equilibrium conditions were established in the flume to simulate those conditions at the cobble bars in the field (including maximum bedload transport rates), the bed surface was approximately 75% cobbles and 25% sand (Photo 4). Where sand waves were found, the bed was 80 to 90% sand with only the large cobbles exposed. Even more prominant than the waves were strings of sand, parallel to the flow direction. These were observed in the field depicting high rates of bedload transport.

For the second test of the flume study, a six inch bed of sand was laid over the cobble substrate. During succeeding flume runs the sand bed was removed. Various bedforms were observed for different runs at different locations in the flume test section. In the lower regime, ripples and large dunes were noted; in the upper regime, the bed planned out with high transport rates (Photo 5). The sand creating the bedforms was significantly coarser than the original sand laid on the cobble bed. With several high velocity runs, the layer of sand and all the bedforms were removed and the cobble bed was once again exposed. Sand was removed progressively from upstream to downstream.

Sand is scoured out from between the cobbles as a result of turbulent bursts in the interstices. Vortex events were irregular and observed to be strongest where several cobbles, stacked on top of each other, protruded above the average height of the cobble bed. A scour pit developed beneath these stacks of cobbles, but was occasionally filled in when a dune bedform passed (Photo 6). The sand could be scoured to maximum depth slightly greater than one median cobble diameter below the surface. Velocities in the cobble interstices were too small to entrain the larger sand sizes long enough to secure passage between the cobbles and back into the main flow zone.

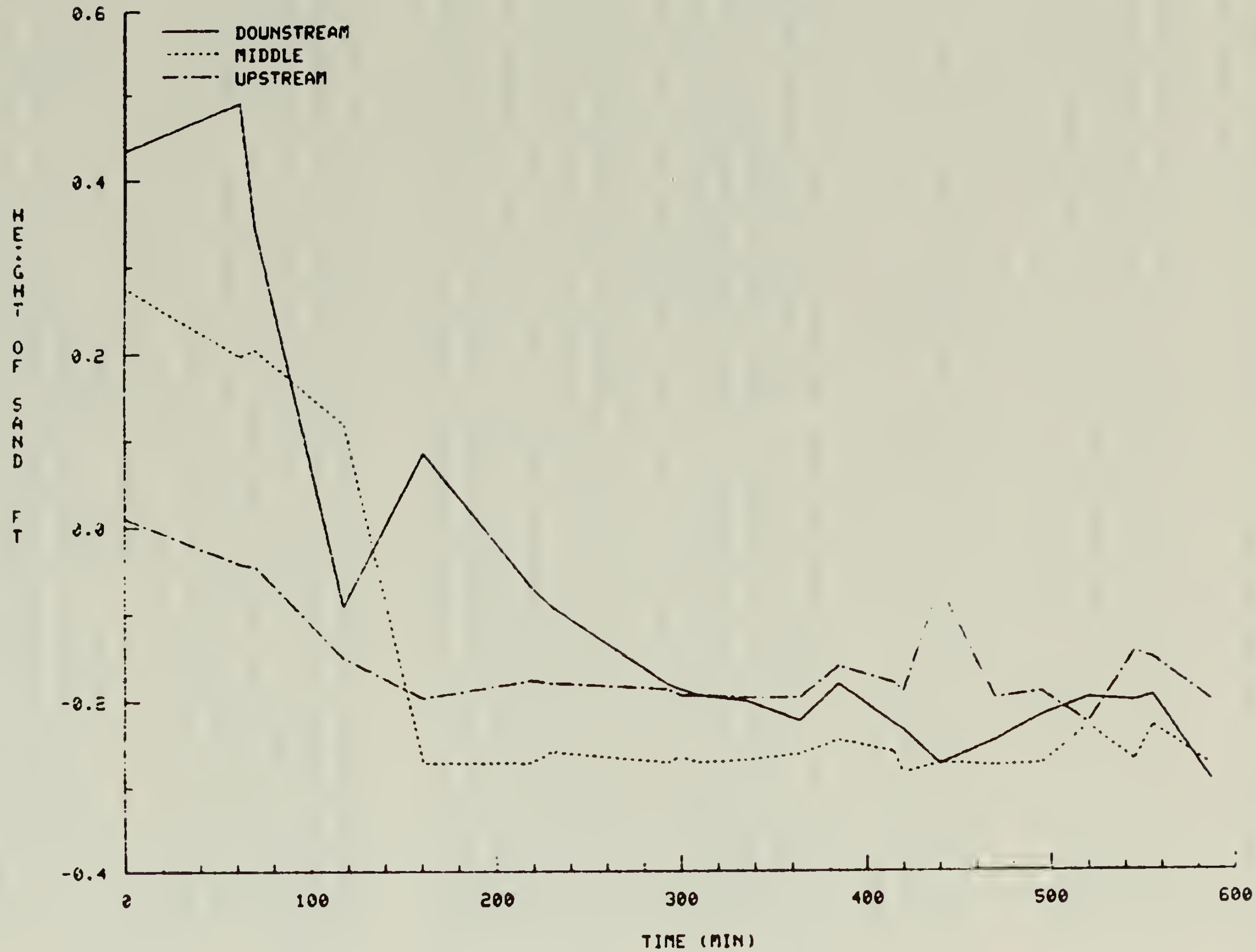
Figure 23 shows the rate of sand removal from the cobbles. A state of equilibrium was reached when the sand level was approximately one cobble diameter below the cobble surface. This level fluctuated with a passage of a sand wave by the point of observation. The three stations all displayed a similar response, reaching an equilibrium level approx-mately 160 minutes after the test was initiated. It is postulated that

Photo 3. Helley-Smith Sampler Positioned for Bedload Collection, Physical Model Study

Photo 4. Equilibrium Conditions of Sand and Cobble Substrate, Physical Model Study

Photo 5. Sand Dune Formation over the Cobble Substrate, Physical Model Study

Photo 6. Sand Scoured from the Cobble Substrate, Physical Model Study



SAND LEVEL IN RELATION TO TOP OF COBBLES

PHYSICAL MODEL STUDY

shear stresses large enough for incipient motion of the median cobble size particle are necessary to scour the sand level to greater depths. In the field, the sand level was approximately one-half to one median cobble diameter below the surface of the cobbles.

Dynamic Processes of Sand Transport over Cobble Substrate

The following discussion applies the results and observations from the physical model study to the field conditions. The effects of deposition of excessive amounts sands and fine material on the cobble substrate can be severe, limiting the aquatic insect population, reducing the capacity for spawning, and reducing the channel carrying capacity. The processes which insure a sand free cobble substrate are closely linked to a seasonal hydrograph shape and duration. The cobble bars have evolved upstream of wide bends to produce relatively short riffles of steep slope and high velocities that prohibit sand deposition. The pools upstream of the riffles have a sand substrate whose bed elevation fluctuates to seek equilibrium levels. The pool bed will scour at peak flows and will aggrade at low flow. There is evidence to suggest that the sand will migrate from a riffle to a pool during the base flow period (Rosgen, 1982).

On the rising limb of the hydrograph, sands are deposited in the interstices. These sands are interchanged between the bed and the suspended zone for discharges less than bankfull. Depending on the supply-capacity relationship, either deposition or scour could be occurring. Coarser sand sizes are transported as bedload in tortuous paths around the cobbles. When the cobbles move, the sand, of course, is washed from the interstices and may completely be removed from around the cobbles. At that point, sand will be released only when one of the armor particles is moved. Rearrangement of the cobbles will result in more stability of the armor layer. On the falling limb, the armor layer becomes a trap for sands until finally, the sand reservoir is again filled. Without cobble movement, sand will be scoured only to a depth of one-half to one median cobble diameter below the cobble bed surface.

It was observed that at peak flows, portions of the cobble substrate were covered with sand to depths of one foot or more. These channel areas, outside the thalweg, are subjected to deposition as the sediment supply approaches transport capacity. Discharges of one-half the incipient motion of the armor layer will be capable of extracting sands and fines from the cobble substrate (Milhous, 1982). This corresponds to roughly the effective discharge for the Yampa River.

Mathematical Model Study

A quasi-steady water and sediment routing mathematical model was developed to simulate sediment transport in the cobble reach of the Yampa River. The field investigation of hydraulics and sediment transport was designed for the purpose of mathematically modeling a portion of the river to predict the river's response to various scenarios of simulated water and sediment discharge. Steepness precludes the necessity of modeling sediment transport in the first twenty miles of the canyon. A portion of the riffle-pool, cobble bar reach from river mile 16.5 to 20.5 was delineated for modeling.

The sediment supply for the model was the 1983 measured sediment data at Mathers Hole. Two cross sections downstream were surveyed as intermediate cross sections to the modeled area. Eight cross sections were monitored at the cobble bar area at river mile 16.5. Five of the eight were surveyed over the cobble riffle and three through the pool upstream (see Figure 3). In all, approximately one and one eighth miles of the four mile cobble reach were modeled. The model reach contained 3 riffles and 3 pools. The last riffle-pool sequence was modeled in its entirety. This sequence represents the complete range of hydraulic and sediment transport conditions and processes that are found in the four mile reach.

The model is constructed of a series of components, which have been universally applied in engineering predictions of sediment transport. It preserves continuity by keeping a budget of the incoming sediment supply, the transport capacity and sediment deposition or scour in each individual reach.

The routing model is designed for determining channel aggradation and degradation in a river system. The river is divided into a series of computational reaches with similar hydraulic and geomorphic characteristics. Hydraulic conditions for each reach are calculated using the well-known and widely applied U.S. Army Corps of Engineers HEC-2 water surface profile computer program. The computed hydraulic conditions are then used to calculate sediment transport capacity for each subreach in the downstream direction. The sediment transport capacity is compared with the sediment supply from the previous subreach and the resulting aggradation or degradation is uniformly distributed both laterally and longitudinally in the reach.

The input discharge hydrograph is discretized into a series of time steps; each step represents a period of steady discharge. The sediment supply to the first cross section is similarly discretized for the same time steps. A new value for water and sediment discharge can be inputed with each time step to simulate the gradually varied flow condition. A description of the sediment transport processes, model assumptions and model calibration are presented in Appendix B.

The results of the mathematical model study was a minimum streamflow hydrograph based on the predicted aggradation/degradation response to reduced water discharge. The minimum streamflow hydrograph was contructed to insure that a relatively sand free cobble bed is maintained in the modeled reach during the period from mid-July through mid-August. This criteria should be met on an annual basis for any given sediment supply scenario. The sediment supply to the upstream cross section, represented by a sediment input hydrograph, governs the resultant shape and timing of the simulated minimum streamflow hydrograph. Numerous sediment supply scenarios and water discharge hydrographs were tested utilizing both sediment-water discharge regression relationships and sediment hydrographs. In the final analysis the simulated hydrograph was based on the 1983 measured sediment load at Mathers Hole.

Combining the historical mean daily discharge with the simulated daily discharge, whichever is less, a composite hydrograph is developed (Figures 24-30). The results are presented in Table IX. The minimum streamflow hydrograph has the following components:

Baseflow (August 16 - March 21)

Of the three periods of record analyzed, water years 1922-83, 1922-38 and 1941-83, the mean baseflow (367 cfs) of the 1941-83 period was chosen as reflecting the post-expansion conditions in the Monument.

Rising and Recessional Limbs (March 22 - July 12)

This portion of the hydrograph was defined by the criteria for maintaining the river mile 16.5 cobble bar essentially free of sand in July and early August.

Colorado Squawfish Spawning Flows (July 12 - August 15)

The PHABSIM computer model predicted 700 cfs to be the optimal flow for spawning.

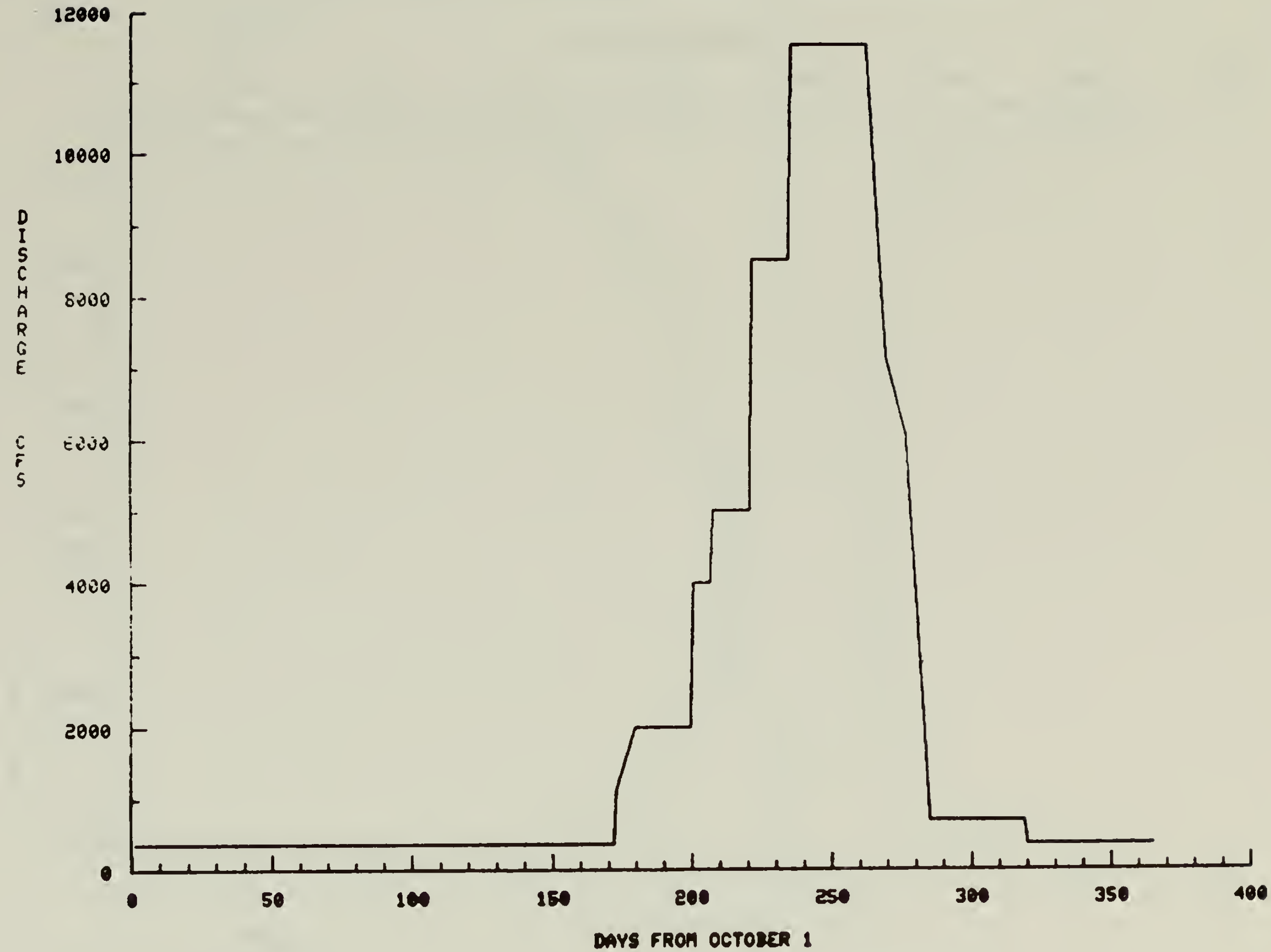
Peak Flow (May 24 - June 20)

The peak flow of 11,500 cfs is the computed effective discharge at Mathers Hole based on sediment rating curves. A channel flushing flow of 48 hours of natural peak is included in the composite hydrograph. When the simulated discharge equals or exceeds the 11,500 cfs peak, then the actual peak discharge and next daily discharge less than or equal to 21,000 cfs is included in the simulated hydrograph. This constraint is reflected in Table IX in computing the composite volumes but was not used in the computer model.

The various components of the hydrograph are connected by step increments. One week steps were utilized in the model. A single value of water and sediment discharge representing the average for the week was associated with each step. This methodology does not allow for rapid changes in discharge. Only general aggradation and degradation is analyzed by the model; local scour, storm inflow, and hydrograph fluctuations are neglected.

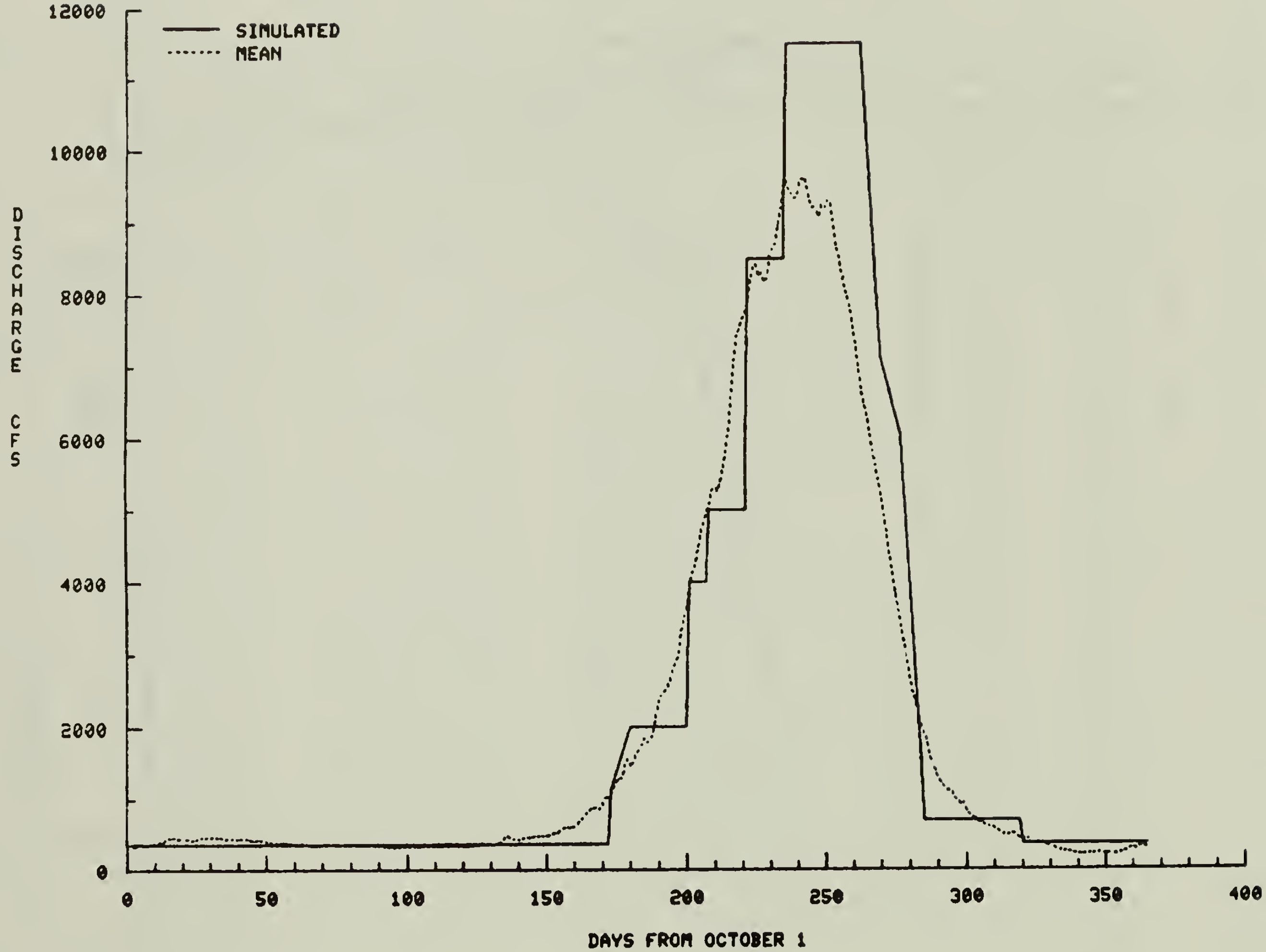
Cross section subreach 5 (Figure 3) was determined by the model to be sensitive to aggradation and degradation of transported sand. . It is also the reach where substantial amounts of aggradation could influence distribution of water discharge around the cobble island. The next subreach upstream of cross section 5 is predominantly sand bed and the downstream reach, mostly cobbles.

Water discharge input was varied to show how sensitive each subreach was to sand deposition. Incremental discharges were input until most of sand deposited is removed and does not exceed one-half of the median cobble diameter in thickness after July 11th. Figure 31 shows the bed elevation response to the simulated discharge hydrograph at subreach 5. Sand is deposited during the rising limb of the hydrograph and removed during the recessional limb.



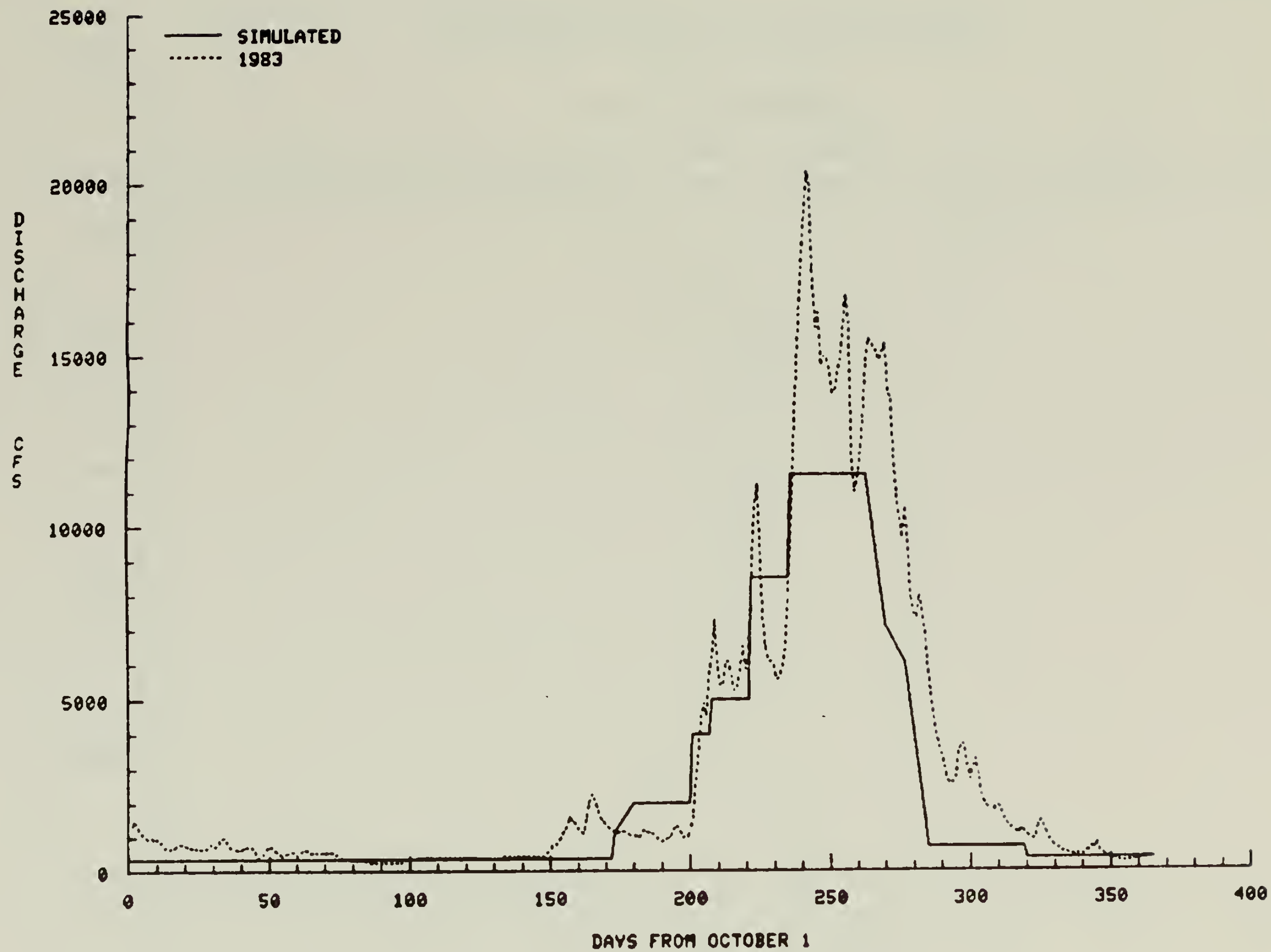
SIMULATED HYDROGRAPH

Figure 24



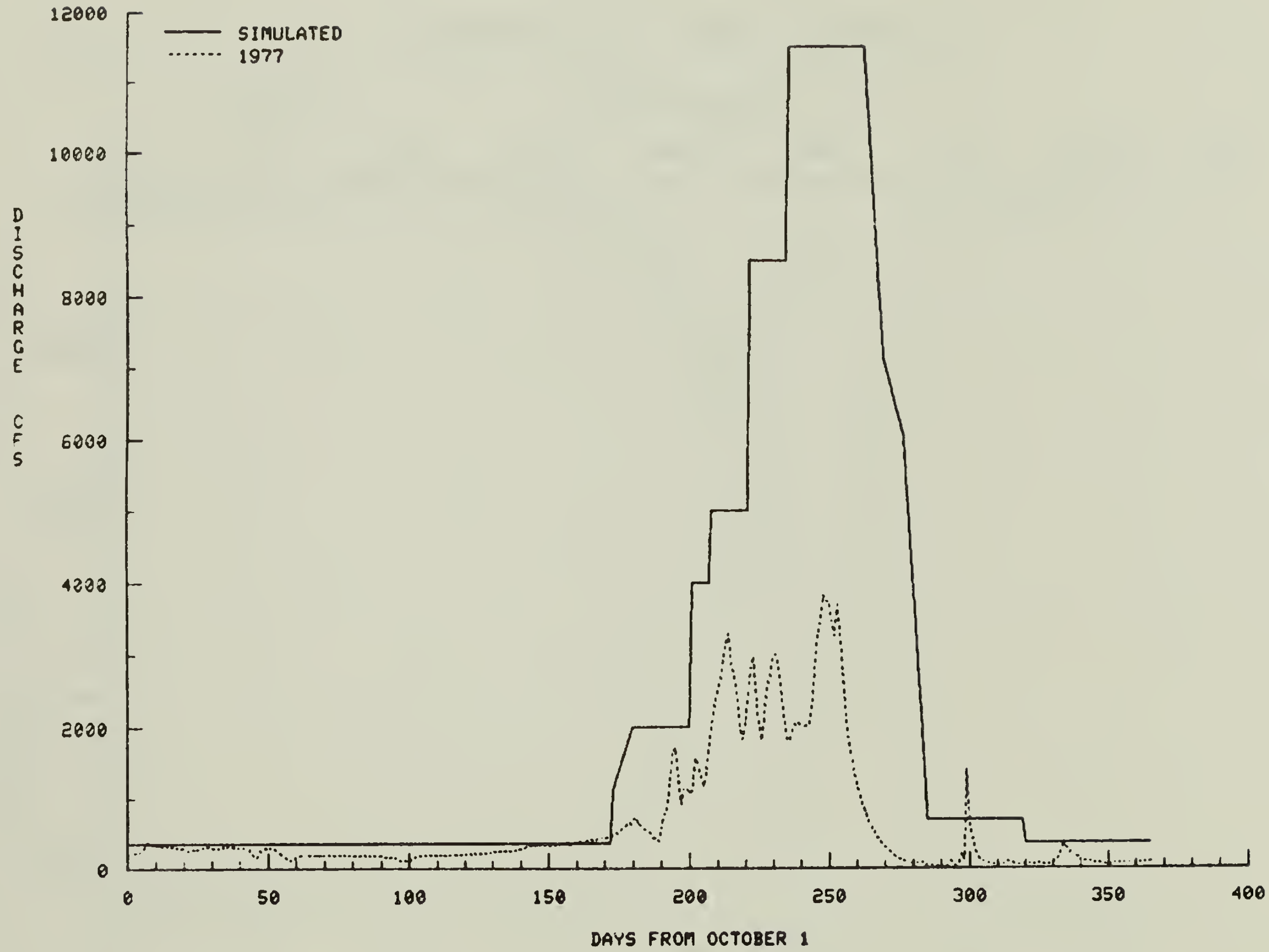
SIMULATED AND MEAN ANNUAL HYDROGRAPHS

Figure 25



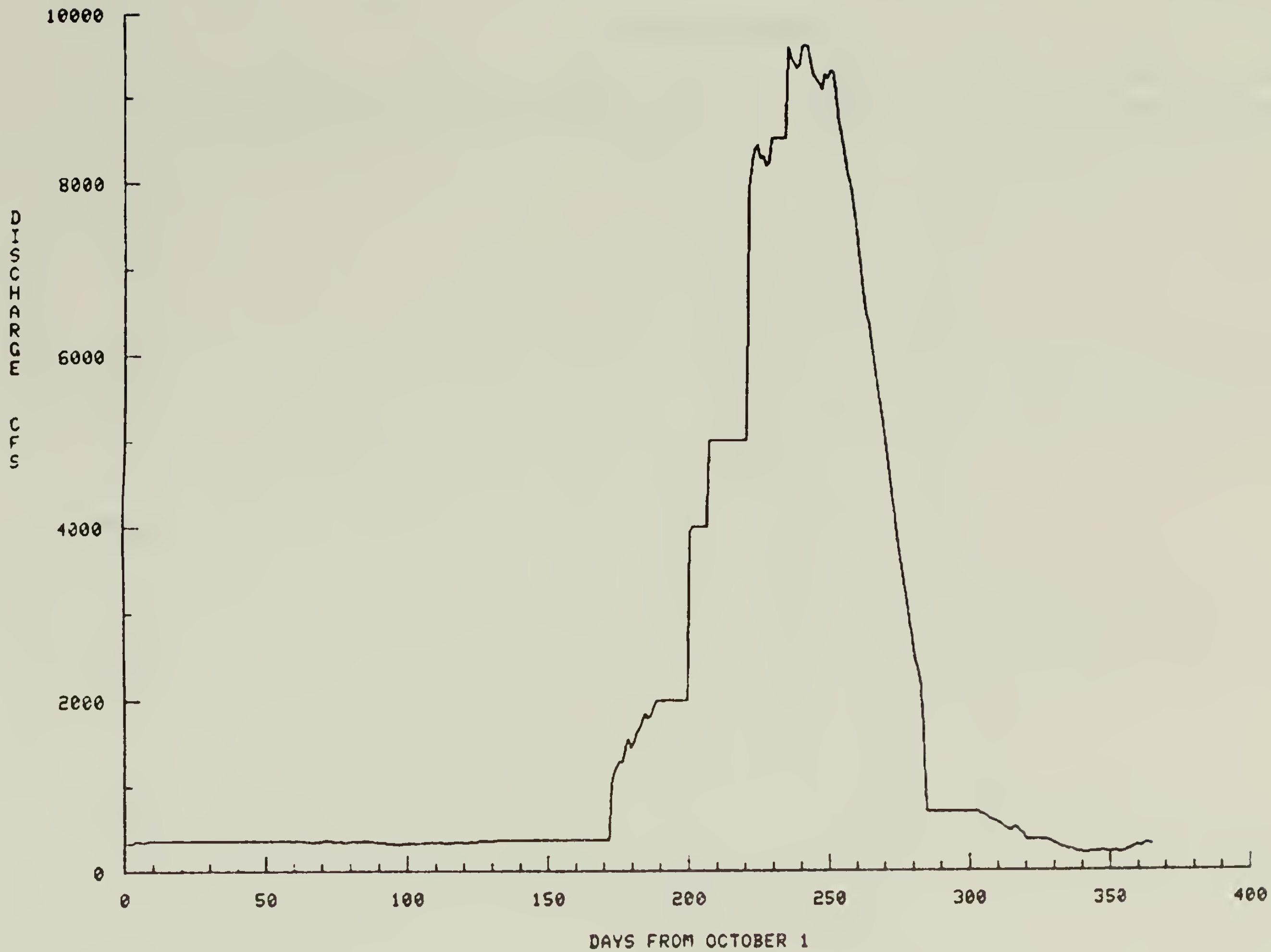
SIMULATED AND 1983 HYDROGRAPHS

Figure 26



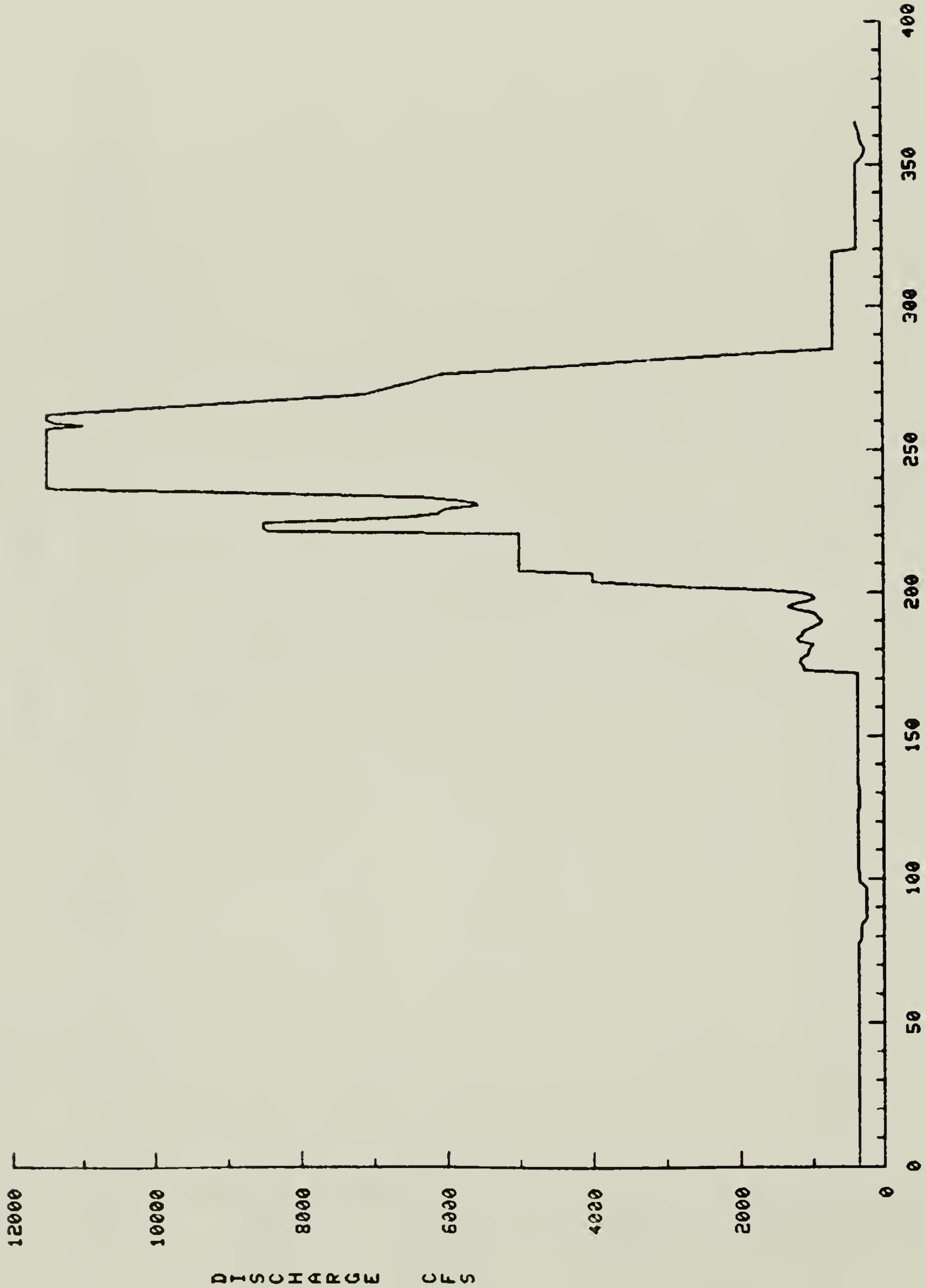
SIMULATED AND 1977 HYDROGRAPHS

Figure 27



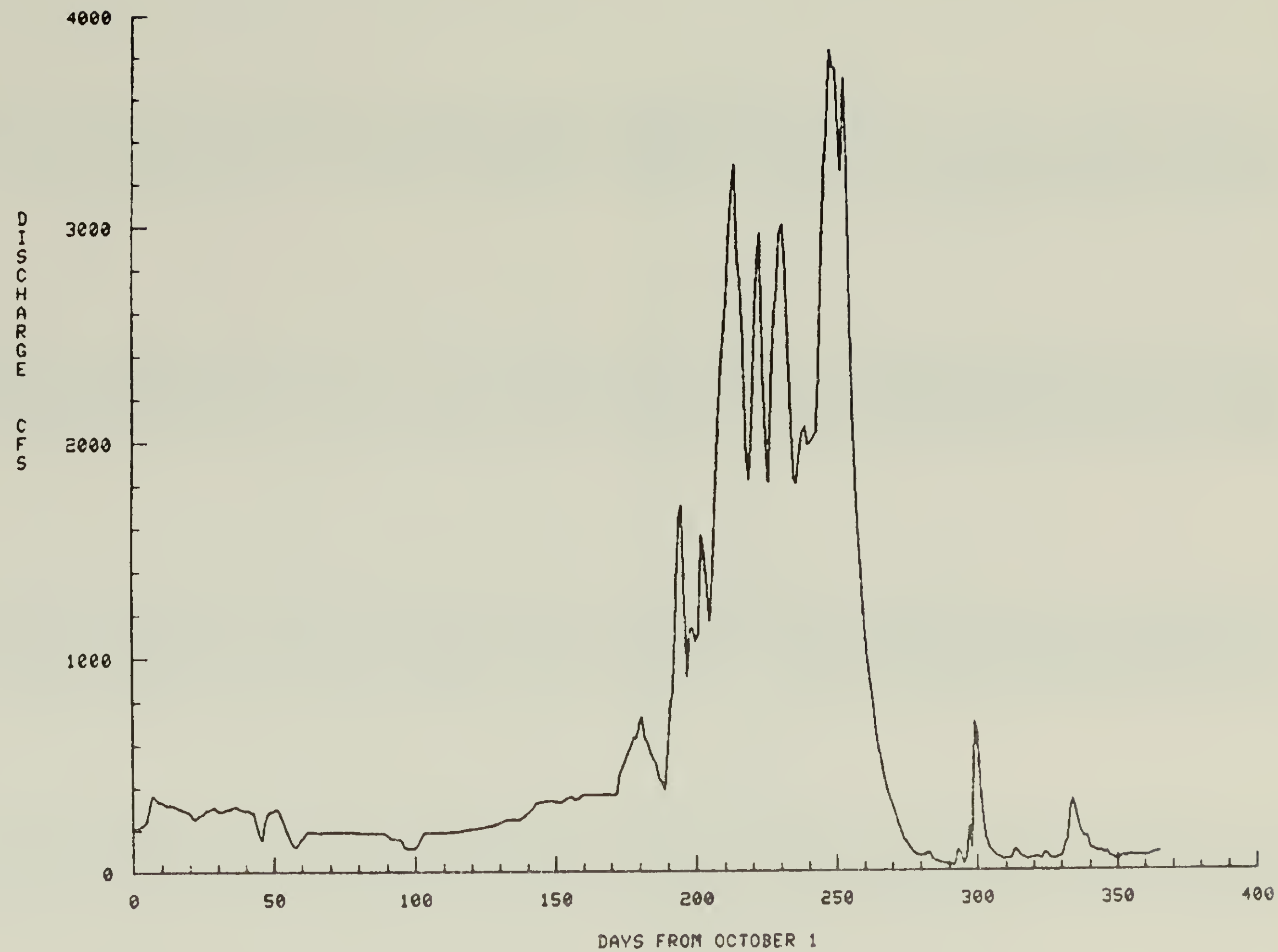
SIMULATED AND MEAN ANNUAL COMPOSITE HYDROGRAPH

Figure 28



SIMULATED AND 1983 COMPOSITE HYDROGRAPHS

Figure 29



SIMULATED AND 1977 COMPOSITE HYDROGRAPH

Figure 30

Table IX. Historical and Composite Hydrograph Volumes

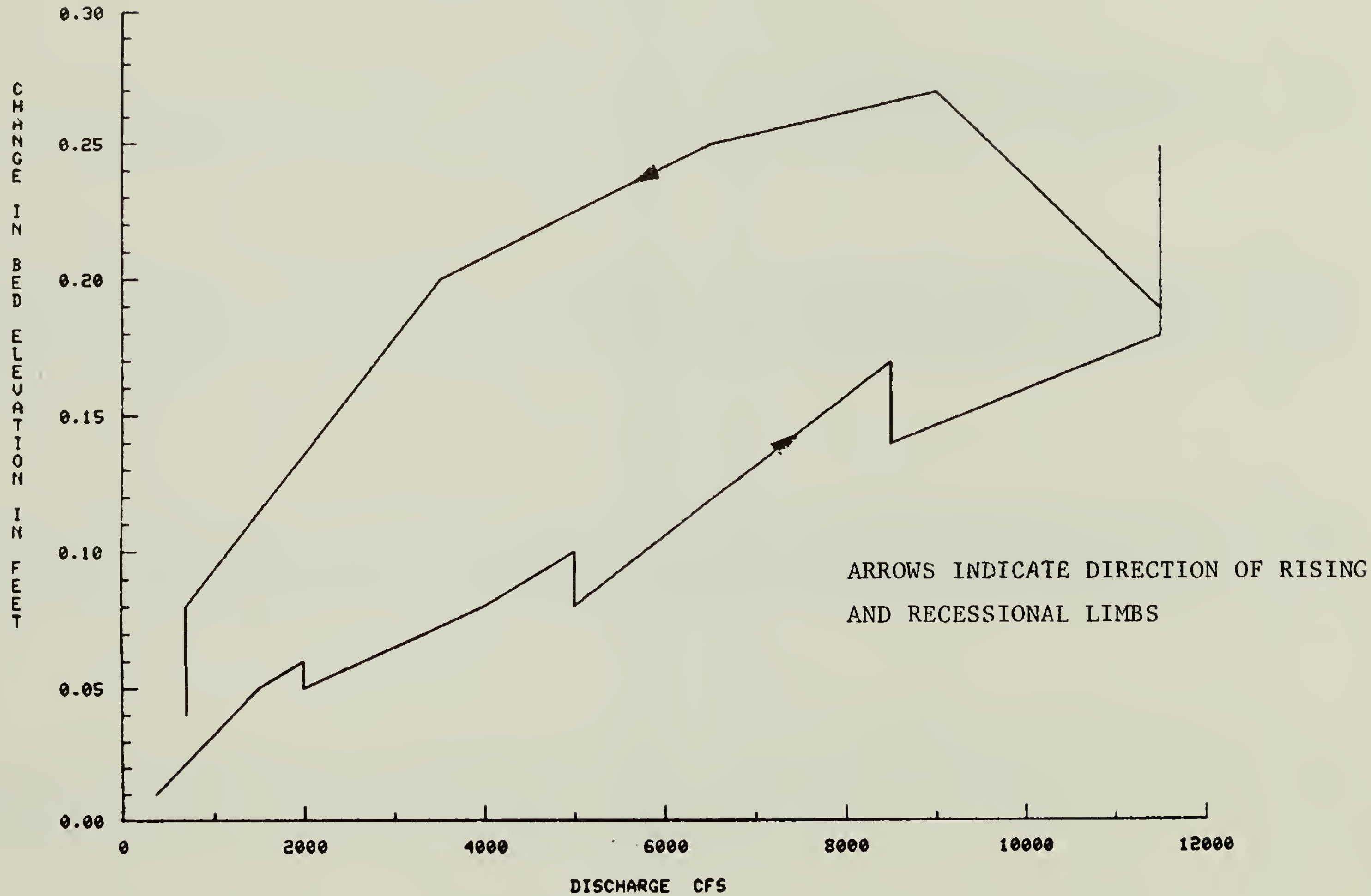
Water Year	Annual Volume (acre-feet)	Composite* Volume (acre-feet)	Surplus Volume (acre-feet)
1922	1584567.	1373542.	211025.
1923	1838252.	1492852.	345401.
1924	1347465.	1188158.	159307.
1925	1408446.	1144597.	263849.
1926	1691386.	1243645.	447741.
1927	1887604.	1455036.	432568.
1928	2106429.	1438478.	667952.
1929	2902553.	1666846.	1235707.
1930	1359346.	1025009.	334337.
1931	1265287.	1024807.	240480.
1932	2144967.	1536915.	608052.
1933	1599209.	1399347.	199861.
1934	454095.	442003.	12091.
1935	1120021.	1099329.	20692.
1936	1508971.	1149219.	359751.
1937	1426433.	1203835.	222598.
1938	1708732.	1362918.	345813.
1939	1233386.	998250.	235136.
1940	1106580.	989908.	116671.
1941	1384672.	1172445.	212227.
1942	1649526.	1324488.	325038.
1943	1244955.	1071605.	173350.
1944	1241415.	1190361.	51053.
1945	1722819.	1391472.	331348.
1946	1179419.	980583.	198836.
1947	1777476.	1372634.	404842.
1948	1466055.	1181326.	284729.
1949	1857943.	1540234.	317709.
1950	1393951.	1272148.	121803.
1951	1310703.	1256181.	54521.
1952	2175005.	1435249.	739756.
1953	1097929.	1077069.	20860.
1954	700438.	685484.	14954.
1955	1005751.	945643.	60108.
1956	1443543.	1173840.	269702.
1957	2289240.	1519630.	769610.
1958	1693288.	1292853.	400435.
1959	1029978.	999768.	30211.
1960	1310152.	1078477.	231675.
1961	792112.	770351.	21761.
1962	2060738.	1284737.	776001.
1963	833860.	805159.	28701.
1964	1184427.	1112846.	71581.
1965	1793325.	1473791.	319534.
1966	1008993.	794151.	214843.
1967	1253888.	1189893.	63996.
1968	1622582.	1445549.	177033.
1969	1508031.	1213968.	294062.

Table IX. Continued.

Year	Annual Volume (acre-feet)	Composite* Volume (acre-feet)	Surplus Volume (acre-feet)
1970	1869818.	1497743.	372075.
1971	2112790.	1571295.	541495.
1972	1266828.	1107146.	159682.
1973	1751740.	1429656.	322085.
1974	1956125.	1453260.	502865.
1975	1639329.	1373772.	265557.
1976	1207034.	1116926.	90108.
1977	448427.	445801.	2626.
1978	1958202.	1562967.	395234.
1979	1727802.	1449511.	278291.
1980	1835731.	1449718.	386013.
1981	802459.	776259.	26200.
1982	1943124.	1564392.	378731.
1983	2246512.	1554124.	692388.
Average	1507933.	1219987.	287946.

Volume of the simulated hydrograph is: 1644185. acre feet

*Composite volume is the summation for the year of the daily discharge or the simulated daily discharge whichever is less.



AGGRADATION/DEGRADATION 1983 SIMULATED HYDROGRAPH VERSION III-4-5

Figure 31

Table IX reveals the relationship between the simulated hydrograph and all the years of historical data. The first column is the combined Lilly and Maybell gaging stations annual volume. The volume of the simulated hydrograph without the 48 hours of natural peak is 1,644,185 acre-feet listed at the bottom of the table. The composite volume is the summation of the minimum of the actual daily discharge and the simulated hydrograph daily discharge. This composite (column 2) includes the natural peak flushing flows. The final column represents the volume which is the difference between the actual and the composite discharge which remains for possible depletion from the river. This analysis indicates that an average of 1,220,000 acre feet annually are required to maintain the channel substrate in the present condition. This compares with the average annual volume of 1,508,000 acre feet, leaving a surplus of 288,000 acre feet.

Minimum Streamflow Hydrograph.

A minimum streamflow hydrograph has been designed to sustain the processes and conditions vital to channel morphology in the Yampa Canyon. This hydrograph was formulated on the basis that the cobble bed remain essentially free of sand during the period in July and August when spawning of the Colorado squawfish has been observed. The most sensitive subreach of the total modeled reach, an observed site of spawning, was examined after each computer simulation. This cross section at the upstream tip of the cobble bar at river mile 16.5 was permitted to be completely inundated with sand during the simulated peak. The deposited sand was then scoured off to a depth of one-half cobble below the apparent bed surface. The simulated hydrograph, therefore, allows sand deposition, but its subsequent removal maintains a sand-free cobble substrate during the months of July and August.

The shape and duration of the simulated hydrograph was dictated by the input sediment hydrograph. The 1983 measured sediment data at Mathers Hole constitutes the best available data on which to base the simulated hydrograph. Since the data was measured at the initial upstream cross section in the modeled reach, no assumptions regarding travel time or sediment size distributions are necessary. The 1983 data represents one of the highest peaks and largest annual volumes on record. It was also a late runoff season. Twenty-eight percent more sand sediment was measured at Mathers Hole than the combined worst historical years on record from the upstream gaging stations. Measured data on the largest sediment discharges were collected in late June and July. These sediment discharges put the most severe demands on the system to keep the cobble bed free of sand.

The final simulated hydrograph is a minimum hydrograph required to transport the 1983 measured sediment load through the cobble reach with only minor net sand deposition. The hydrograph consists of a substantially smaller peak and volume than the 1983 hydrograph which actually delivered the sediment to Mathers Hole. It is assumed that measured sediment load would be delivered to Mathers Hole even with the reduced flows. It is also assumed that the rate at which sediment is supplied from the upstream watershed will not accelerate in the future. Since the 1983 sediment load is conveyed through the cobble reach, and since no reduction in supply from the Little Snake is anticipated, it is appropriate to assume that delivery of the sediment load is possible for reduced discharges.

The simulated hydrograph has a peak flushing component for 48 hours that equals or exceeds 11,500 cfs but is less than 21,000 cfs. The natural peak discharge is recommended as a flushing discharge that will retard vegetative encroachment, replenish beach and bar areas with sand, and scour areas of sand deposition in the cobble reach. Any seasonal storage of sand in Deerlodge Park would be minimized. While flows greater than 21,000 cfs may occur, this discharge is sufficient to entrain small cobble particles, rework and maintain the cobble bars and generally insure that no major changes in the channel morphology are forthcoming. The 21,000 cfs is slightly below bankfull discharge and below the incipient motion of the median cobble diameter and should not result in any catastrophic channel change while keeping the natural processes in the channel active.

Probable Effects of Reduced Annual Flow

Prediction of the channel response to reduced flow scenarios is very subjective in the absence of knowledge regarding shape and duration of the hydrograph or upstream sediment supply. Entertaining several sweeping assumptions, however, some general river responses to reduced discharge can be postulated. Both the long- and short-term response are addressed in terms of channel morphology, vegetative encroachment, and sand deposition on cobble substrate (see Flow Chart, Figure 32).

In 1977, the lowest year of volume and peak discharge on record, approximately 450,000 acre feet flowed through the Yampa Canyon. In analyzing this hydrograph, the discharge exceeded the mean base flow of 367 cfs from March 9 to June 24, a total of 109 days. The peak discharge of 3821 cfs occurred on June 5. The discharge fell below 700 cfs on June 21 and below 100 cfs on July 4. A volume of 500,000 acre feet of water is equivalent to a constant daily discharge of 700 cfs for the entire year. Comparably, a simulated hydrograph with a baseflow of 367 cfs could be formulated with a peak discharge of 11,500 cfs. If the peak of 11,500 cfs flowed for x days, then the number of days the discharge would exceed the baseflow would be given by: 21 - x, assuming a linear rising and recessional limb.

During the short-term, one to five years, the adverse effects of a simulated hydrograph would be relatively minor. Some vegetative encroachment into the zone below bankfull discharge and on the beaches would be expected. The maximum period that the peak discharge has not exceeded 11,500 cfs is 3 years from 1959 through 1961. With a peak of 11,500 cfs for seven days, the channel should maintain its suitability as fish spawning habitat in the cobble reach. Vegetation growth on the cobble bars may be wide spread but would not effect the riparian zone below the level of 11,500 cfs. Any adverse effects could be negated by later peak discharges approaching natural conditions. Obviously, the effects of the 1977 low water year have been obliterated.

FLOW CHART: EFFECTS OF ALTERED FLOW REGIMES ON HYDRAULIC PARAMETERS

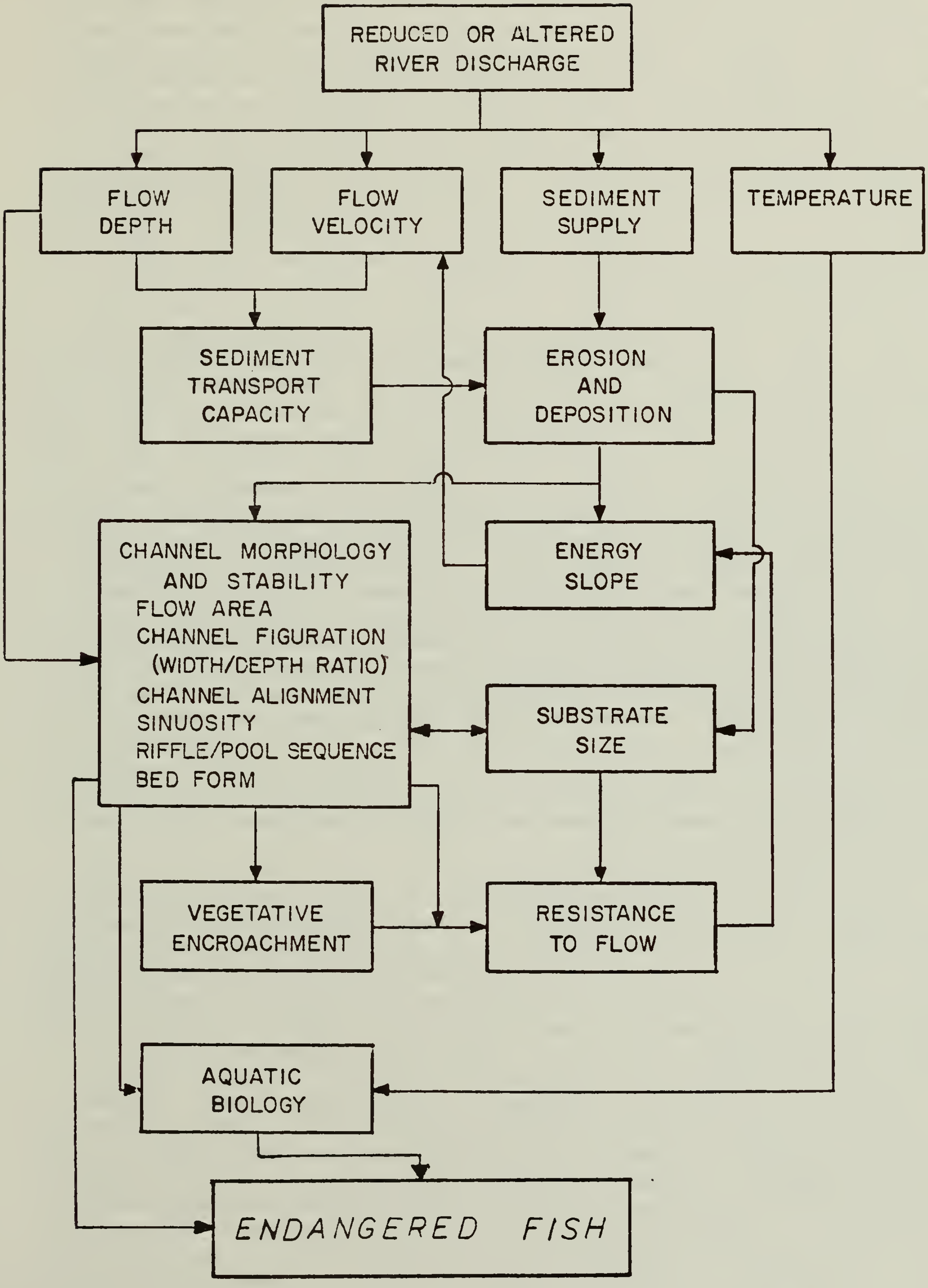


Figure 32.

With a controlled hydrograph of a constant discharge of 700 cfs, the effects would be more pronounced. Vegetative encroachment should be extensive in this case and sand deposition in the cobble reach would occur if the sediment stored in the Deerlodge Park reach became significant. Storm events on the Little Snake drainage or in Deerlodge Park area would produce short time-to-peak hydrographs of relatively small discharges of several thousand cubic feet per second. Such events in a reduced flow scenario would be detrimental, delivering large quantities of sand to the cobble reaches, filling in the pools and possibly covering some of the cobbles. This phenomena would most likely be progressive, filling the upstream canyon pools initially. Again, the adverse impacts may be reversed by peak discharges on the order of magnitude of the natural peaks.

The long-term river response is more difficult to predict. The Deerlodge Park reach after the confluence of the Little Snake River, being an alluvial channel, is the most sensitive reach to any changes in discharge which deviate from a natural flow hydrograph. Depleted flow from Yampa River without corresponding discharge depletions from the Little Snake would generate the most severe channel response. Hydrograph shape and the temporal relationship between the Yampa and Little Snake are the key factors. Qualitatively, river channel response may include: change in flow area, stage, energy slope, channel stability, and possibly river form. Sediment loads from the Little Snake would deposit in Deerlodge Park aggrading this four mile reach of river. The bed slope would increase until the resultant hydraulic conditions could transport all of the incoming sediment supply from the Little Snake. Vegetative encroachment would ensue, stabilizing bars, reducing channel width and carrying capacity in some reaches. The river stage at higher flows would be increased and in some areas may result in overtopping the banks. In very wide sections, the change in slope may create alternate bed forms, varied flow resistance, and quite probably a more braided river than already exists at low flow. Here channel stability would be adversely effected. Overall, bed material size would decrease in this reach.

Relatively minor changes would occur in the first twenty miles of the canyon. The most severely effected areas would be beaches contiguous to the five or six pools upstream of rapids. These areas would be stabilized by vegetation growth. The upland vegetation zone would be more inaccessible in these pool areas similar to that presently existing at Big Joe Rapid. Sand beach and bar areas not stabilized by vegetative encroachment would be eroded by eddy velocities.

Some long-term channel adjustment in the cobble reach to either a constant or varied discharge should be expected. A constant discharge would effectuate a more severe response than the varied discharge. With reduced discharge, channel stability would increase, loss of channel carrying capacity would be negligible, and the effects on stage would be minor. The critical responses would be the reduction in bed material size distribution, sand deposition in the pool reaches and vegetative growth on the exposed cobble islands. Some of the cobble reaches would still be free of sand, but the majority of this reach would be lost as spawning habitat from a combination of a reduction in flow area and sand inundation of the cobble substrate. With stabilization of the channel, cobble bar evolution would cease, side channels would be closed permanently, and a single higher velocity channel would develop. The minimum stream energy required to mobilize the cobble substrate would never be exceeded. All of the dynamics of reworking the cobble islands and changing the shape and orientation of the bars would be forfeited. Water surface slope would increase above the cobble riffles and an alternating sand-cobble bed similar to the reach above Warm Springs Lake would develop. Average water temperatures in the Yampa Canyon would increase in the summer months; however, the Yampa's warming effect on the Green River water temperature would be diminished because of the reduced discharge.

The long-term effects on habitat in the cobble reach is functionally linked to the constraints imposed on sediment supply from the Little Snake and the resultant Yampa River channel response in Deerlodge Park. Storm events of uncontrolled discharge would compound the problems in the canyon by introducing large sediments loads.

CONCLUSIONS

The minimum streamflow for natural maintenance of the stream channel morphology and riparian habitat in the Yampa Canyon encompasses a range of discharges which will transport the bulk of the total annual sediment load, inundate the active channel area, maintain existing substrate characteristics and sustain the dynamic processes forming the integral features of the channel. Based on the results, the required minimum streamflow is defined by a hydrograph, whose components include baseflow, rising and recessional limbs, and a peak discharge. The minimum streamflow hydrograph, considered critical for channel stability was determined using widely accepted sediment transport and hydraulic principals.

The 1983 expanded sediment sampling program at Mathers Hole was designed to accurately defined the various components of the sediment load on both the rising and recessional limbs of the seasonal hydrograph. The results, in terms of the sediment discharge versus the water discharge regression relationships, display the high reliability of sampling techniques and site selection. The ability to mathematically predict river response to altered or reduced discharge is enhanced by the credibility of measured data.

All the sediment transported in the cobble reach is considered as throughput or washload. Except for flows near bankfull discharge, virtually all the transported sediment is sand size particles and smaller. Small gravels are transported as bedload at discharges less than bankfull. This a minute portion of the total load. Near bankfull discharge, small and medium cobbles are moving as bedload. Again, this represents a infinitesimal part of the total load. Although the transported sediment load is large, the river maintains a consistent substrate through a range of flows. Changes in substrate are experienced at peak flows. Sand substrate pools are scoured to cobble or bedrock base at the peak and are refilled with sand on the falling limb. Some channel areas, outside the thalweg, are subject to sand deposition at peak flows as a function of the large transported load.

A distinction is formulated between the effective discharge and the bankfull discharge. The bankfull discharge is the dominant or channel reforming discharge capable of inciting motion of the median size diameter of the bed material in the cobble substrate reach. The effective discharge is defined as the discharge transporting the most sediment over long time period as a product of the sediment load being transported and the frequency of recurrence. Both discharges were utilized in constructing the minimum streamflow hydrograph.

The range of discharges required to preserve these morphological conditions during the summer months of July and August have been predicted using a mathematical water and sediment routing computer model. The results of the simulation are based on the 1983 sediment data measured at Mathers Hole. The range of discharges for channel maintenance is presented in the form of a seasonal discharge hydrograph.

Some general observations of the river response to the large runoff discharge and sediment load by monitoring numerous cross sections located throughout the canyon were reported. The cross sections in the first third of the canyon, the steep reach, had a net loss of sediment. The cobble substrate reach in the middle of the canyon experienced no significant channel changes. The cross sections in lower one third of the Yampa Canyon aggraded. The overall net change in the twenty-one canyon cross sections was slight aggradation.

The physical model study revealed that sand can be scoured from cobble substrate to a depth of one average cobble diameter without cobble mobilization. This scour depth will be less when sizes larger than sand are trapped in the interstices. In the field the cobbles are free of sand to a depth of one-half cobble diameter below the mean cobble surface. The minimum stream flow hydrograph was designed to issure that the cobble bed was free of sand to depth of one-half cobble diameter from July 11 to August 15.

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APPENDIX A

PHYSICAL MODEL STUDY

Range of Simulated Conditions

The primary objective of the flume study was to identify the important processes and flow conditions for which sand is transported over, deposited on and scoured from a cobble substrate. A second objective was to calibrate the collection efficiency of the Helley-Smith bedload sampler on a cobble substrate.

The physical model study was based on hydraulic and substrate conditions of the cobble bar at river mile 16.5. Hydraulic data gathered on this reach during the summer of 1983 has been used to establish the simulated conditions for the flume study. The data collected included cross sectional profiles, velocities, water surface slopes and surface and subsurface substrate particle sizes.

Consultation with biologists assisted in finalizing the range of hydraulic conditions to be modeled in the flume study. A sand-free cobble substrate is the preferred spawning habitat of the Colorado squawfish during the months of July and early August. The modeling parameters were determined from field data collected during the spawning period at moderate to low discharges (generally 500 to 4000 cfs). Depth (1-4 feet), velocity (1-5 fps) and slope were simulated in the flume on a one to one modeling ratio of prototype to model.

Laboratory Facilities

The facilities used in this flume study are located in the hydraulic lab at CSU Engineering Research Center. A 8' x 4' x 200' water and sediment recirculating flume was used in this study. The flume has a variable slope which covers the range the field conditions to be simulated. Three pumps, which can be operated independently, supplied water at a maximum rate of 98 cfs.

The flume was divided into three sections; a roughness section, a test section, and a sediment collection section. Boulders were permanently fixed to first 100 feet of the flume bed to insure fully developed turbulent flow prior to the test section. The test section length was fifty feet. Clean cobbles (62 mm median diameter) from the Poudre River were uniformly distributed on the flume bed to a depth of seven to nine inches (approximately three times the cobble median diameter). The remaining fifty feet of flume were used to store excess fine sediment not recirculated in the system.

Sand was introduced to the system just upstream of the test section. A vibrating sand feeder, located on a stationary platform on top of the flume, supplied sand at varying controlled rates. To uniformly distribute the sand across the channel a shield was mounted beneath the feeder.

A sediment trap was constructed at the end of the test section to collect all the coarse sand moving as bedload over and through the cobbles. The trap was a trough (parallel boards) about one foot wide and 3/4 foot deep oriented 45 degrees to the flow direction. Inside the walls of the trough, a PVC pipe with a narrow lengthwise slit, was installed. Sheet metal covered the trough and directed sediment into the narrow slot in the pipe. The upstream end of PVC slotted pipe was connected to pumping system that siphoned water out of the flume and into the slotted pipe. A sediment tank was connected to the downstream end of the PVC slotted pipe. In this manner water was circulated continuously through the slotted pipe washing any captured bedload particles into the sediment tank underneath the flume. The tank plumbing was valved to bypass the circulating water and sediment when a sample was not being collected.

Data Collection

In all phases of the flume study the following hydraulic data were collected: water discharge, mean velocity, depth, water surface slope, and flume bed slope. Water discharge was monitored by manometers attached to the pipe system of the pumps. The flow depth and slope was also measured with manometers. The average center channel velocity was measured at the 0.6 depth below the water surface with a Price pygmy meter. To check the assumption of a logarithmic velocity distribution, several vertical velocity profiles were measured at various points in the channel. The flume bed slope was surveyed.

The total bedload sediment transport was collected using the trap and storage tank system. During the sampling period coarse bedload particles accumulated in the tank and suspended fine material was ejected with excess water. Increases in the stored sediment were monitored with a point gage. The tank was constructed with plexiglass window to view the sediment as it was deposited. After a sampling run, the sediment was allowed to settle, the bed was leveled and the depth of sediment was measured. The bedload transport was calculated by timing the period of flow to the tank.

To calibrate the Helley-Smith bedload sampler for coarse size sediment moving over a cobble bed, the sampler was operated within ten feet of the trap. The sampler was suspended from a mobile platform and lowered to the bed, resting in midflume for 30 second intervals. Upon raising the sampler the 250 micron mesh collection bag was emptied through the three inch square nozzle into a bucket by flushing it with a hose. Two sets of Helley-Smith samples were collected for each run.

The Helley-Smith technique used in the flume study was the same as that employed in the field. For the purposes of this study the bedload transport rate measured by the trap and tank system is considered the actual bedload transport rate and the Helley-Smith sample is the measured transport rate.

There were three phases in the flume study. The purpose of the first phase is to compare the sampling efficiency of the Helley-Smith sampler on a cobble bed for the desired range of hydraulic conditions. In this phase all hydraulic and sediment data was collected on each run. The first phase consisted of 70 flume runs.

In second phase, the efficiency of the Helley-Smith sampler was calibrated for a range of hydraulic conditions over a sand bed. Again, both hydraulic and sediment data was collected on each run. There was a total of ten flume runs in the second phase.

Scouring processes in a cobble bed inundated with sand were investigated in the third phase. Hydraulic data and Helley-Smith bedload samples were collected for each run. Flow velocities were recorded at two points in the test section. Additionally, the scour of sand from the cobble bed was recorded from observations through the plexiglass flume wall. There was a total of eleven flume runs in the third phase.

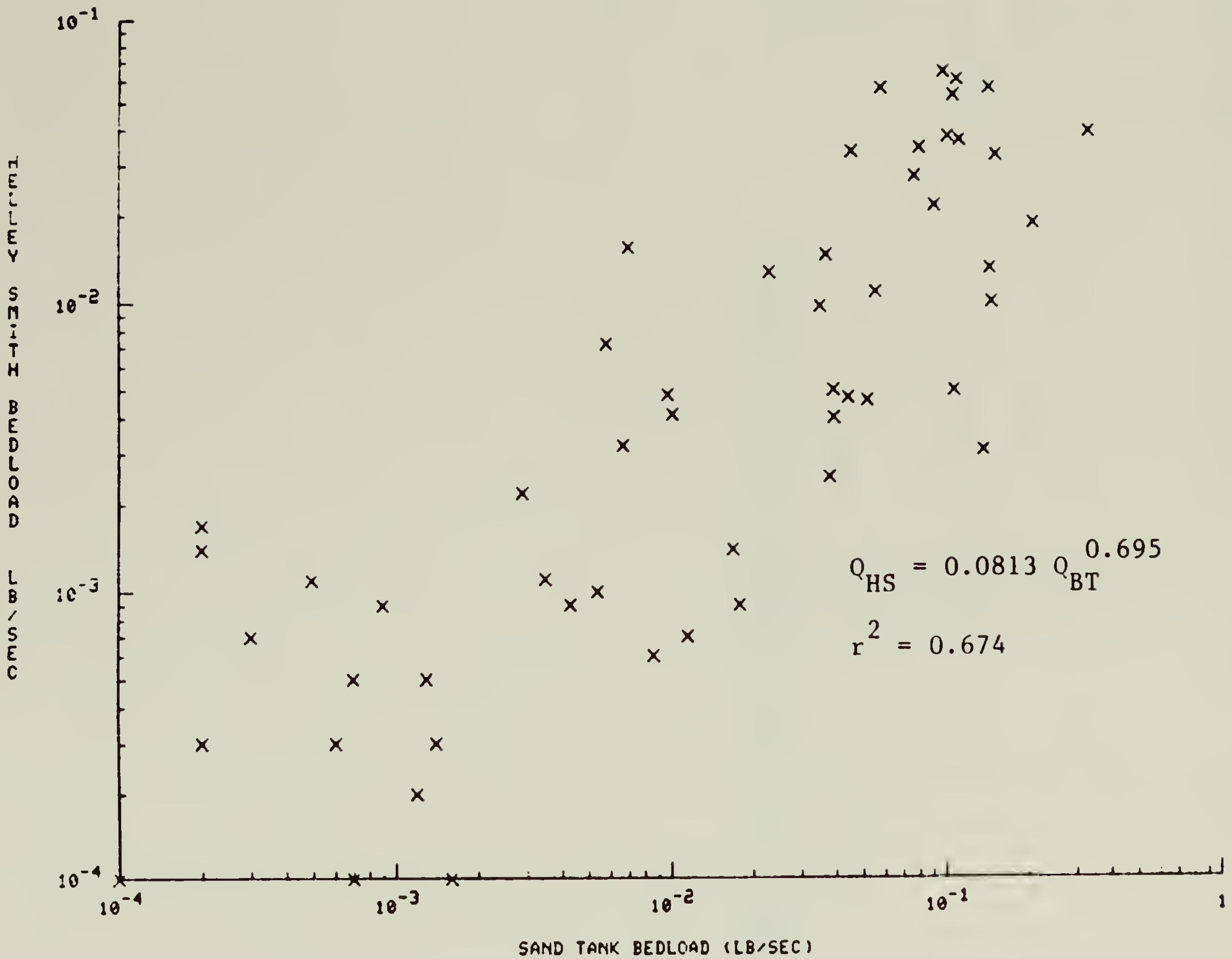
Calibration of the Helley-Smith Sampler

Sand was introduced to the cobble substrate at the upstream limit of the test section. Initially, the sand accumulated directly below the feeder. Once the bed aggraded to a height of approximately the relative roughness of the cobbles, it began moving as bedload into the test section. The sand inundation of the fifty foot cobble test section occurred in the form of a progressive wave. Although some finer sand drifted over and deposited in the bed preceding the coarser sand wave, these quantities were very minor.

Seventy-two sets of two bedload measurements per discharge were made with the Helley-Smith sampler in the flume. The experiments were designed to measure bedload over a range of velocity, depth, and sediment transport conditions. Only sediment moving as bedload was considered in the analysis. Some sediment was transported in suspension but hydraulic conditions limited this load to the smaller size fractions.

The Helley-Smith load (measured bedload) was divided into size fractions and was compared with the bedload captured in the sediment trap (actual bedload). The results show very large scatter in the data (Figure 33). For the larger size classes the actual bedload exceeded the measured bedload in 84% of the runs. Conversely, for finer sediment sizes greater quantities were measured with the Helley-Smith sampler. The sediment trap was less effective in capturing the smaller size fractions which may have passed over trap opening in suspension. Table X shows that the best correlation between the Helley-Smith sampler and the total bedload moving in the flume is found for the middle range of size fractions.

The coarser size bedload moved around and through the cobbles below the apparent bed surface defined by the average height of the cobbles. In this manner, the sand snuck under the sampler, but was collected in the trap. As result, the actual bedload was consistently greater than the bedload measured in the sampler. It was observed that the Helley-Smith load is sensitive to local conditions on the bed with respect to relative roughness, nozzle orientation, and proximity to the sand level in the cobble bed. Often a sand string or wave will pass by the sampler distorting the bedload transport measurements. The sampler was observed



HELLEY-SMITH VS. SAND TANK FOR PARTICLE SIZE 0.00328 FT.

Figure 33

Table X. Calibration of the Helley-Smith Sampler on a Cobble Bed

Representative Particle Size Fraction (ft)	Regression Equation	Coefficient of Determination
.00089	$Q_{HS} = 0.18\ Q_{BT}^{.50}$	$r^2 = 0.52$
.00106	$Q_{HS} = 0.26\ Q_{BT}^{.57}$	$r^2 = 0.53$
.00150	$Q_{HS} = 0.29\ Q_{BT}^{.62}$	$r^2 = 0.63$
.00232	$Q_{HS} = 0.13\ Q_{BT}^{.65}$	$r^2 = 0.64$
.00328	$Q_{HS} = 0.081\ Q_{BT}^{.70}$	$r^2 = 0.67$
.00552	$Q_{HS} = 0.043\ Q_{BT}^{.68}$	$r^2 = 0.66$
.01100	$Q_{HS} = 0.0028\ Q_{BT}^{.36}$	$r^2 = 0.16$

Q_{HS} = Helley-Smith Sediment Load (tons/day)
Q_{BT} = Total Flume Bedload Discharge (tons/day)

to dramatically oversample when placed on a sand bed. It collected large quantities of sand even when no sand was moving into the sediment trap.

On a uniform cobble substrate, Helley-Smith measurements result in underprediction of the actual bedload transport. Irregularity of the bed, both in terms of substrate and relative roughness, improves the reliability of using the sampler in the field. The diversity of substrate permits a wide range of sampling conditions which results in better correlation of bedload with discharge. The Helley-Smith undersamples the coarse material whenever the sampler does not rest directly on the bedload contact surface.

APPENDIX B

MATHEMATICAL MODEL DESCRIPTION

Sediment Transport Processes

A river channel responds with either sediment deposition or scour depending on its ability to move sediment (transport capacity) and the quantity of sediment supplied from upstream sources. When the transport capacity of the river reach exceeds the upstream supply, the flow will remove sediment from the channel bed and banks, expending excess energy in the process. Conversely, if the supply exceeds the capacity, aggradation will change the bed substrate. For the same flow conditions, smaller sediment particles will be transported at larger rates than large particles. Sediment transport capacity, therefore, is best formulated as a function of size fraction of the sediment.

The sediment transport capacity of the bed material load is a combination of two processes, bedload and suspended load. The sediment which moves by the phenomena of rolling or creeping in contact with the stream bed is referred to as bedload. The suspended load consists of sediment particles which are suspended or saltated into the main zone of flow. The bed material load is the summation of the two types of processes. Turbulent mixing and gravity results in a continuous interaction of particles between the bed and the stream flow. Suspended load particles which are not found in appreciable quantities in the bed, are referred to as wash load.

The bedload transport capacity was calculated using the Meyer-Peter and Müller formula. Bedload transport is computed as a function of an exceedance of threshold stream power. This equation is particularly appropriate for channel armoring processes and for streams with a large range of sediment sizes. This is a typical value used for sand size material from the Shield's diagram. In the Meyer-Peter and Müller equation the dimensionless critical shear stress for sand size material is 0.047.

Suspended transport capacity is based on a technique developed by H. A. Einstein which is widely accepted and universally applied. This method integrates a sediment concentration profile as a function of the depth of flow. The bedload layer, as calculated using the Meyer-Peter and Müller formula, is a point of known concentration from which the entire concentration profile may be determined. Turbulent transport theory is the basis for determining the concentration profile shape.

Model Assumptions

Several assumptions are embodied in applying the computer model to the Yampa River. The broadest assumption is the use of the sediment transport models for predicting capacity in a cobble bed stream. Most models have been developed for sediment in alluvial sand bed streams where an infinite supply of sediment is available from the bed. Through the use of the Meyer-Peter and Müller equation and the routing of sediment by size fractions it is possible to predict the phenomena of armoring. The coarsening of the bed surface material through the armoring process limits the availability of the finer subsurface material, and the capacity will exceed the supply.

It is not clear how stream capacity may deviate from theory when the original bed is cobbles. Meyer-Peter and Müller had used gravels and coarse sand to derive their bedload equation. The accuracy of this method will be limited by the correct choice of the critical shear stress parameter in the formula. The critical shear stress parameter was chosen to be 0.047 because most of the sediment load is sand washing through the system. This method of combining bedload and suspended load models represents the best available technology for the prediction of sand transport capacity.

A second major assumption involves the uniform distribution of sediment deposition or scour laterally and longitudinally in the channel. Sediment transport characteristics in each reach are a function of the average hydraulic conditions in the channel. Localized scour and deposition are not reflected by the model.

Hydraulic conditions are assumed to be subcritical and the discharge constant for a given time step. The HEC-2 calculations assume a rigid boundary condition, however, the cross section stations are modified at each time step. The following assumptions are inherent in HEC-2 water surface profile model:

i) The flow is steady and gradually varied.

ii) Hydrostatic pressure distribution exists everywhere in the channel.

iii) The flow is one-dimensional.

iv) The total energy head is equal everywhere in the channel.

v) The channel bed slope is mild.

vi) The channel roughness varies little with stage.

Channel roughness does vary with discharge, it is a limitation of the model not to accomodate changes in roughness values. This limitation will affect the stage at lower flows; however, since the channel configuration is not appreciably modified by aggradation/degradation, the overall affect on sediment transport is assumed to be minor.

The initial channel surface and subsurface bed material for each subreach is represented by a size distribution. Variation of substrate across the channel is neglected. The thickness of the surface and subsurface bed material is specified at the outset of the modeling exercise and is assumed to be of uniform thickness throughout the reach. When the surface layer has been removed, the size distribution reflects the availability of particles from the subsurface material.

Model Calibration

The water component of the model, specifically the HEC2 water surface profile, is calibrated from a knowledge of the peak water surface elevations at each of the eleven cross sections. Since a stage-discharge relationship has been established at Mathers Hole, the channel roughness can be adjusted to give a good estimate of water surface at each cross section and an exact elevation at Mathers Hole, the final upstream cross section.

From observations and cross sections measurements, minor amounts of aggradation and degradation were noted during the 1983 field season. Some small amounts of sand were deposited during the peak discharges. The model was calibrated with the 1983 measured data. The predicted river response was observed in the field; aggradation at Mathers Hole during the peak, degradation of the sand substrate cross section, and general hysteresis loop of deposition and scour (Figure 34).

Mathematical Description

A brief description of the hydraulic and sediment transport equations are presented below. A list of variables appears at the end of the appendix.

The hydraulic conditions were determined with the Army Corps of Engineers HEC-2 backwater profile program developed by Eichert (1976). The basic flow equations employed in the program are:

Continuity equation

$$\frac{dQ}{dx} = q = Vd \tag{1}$$

Energy equation

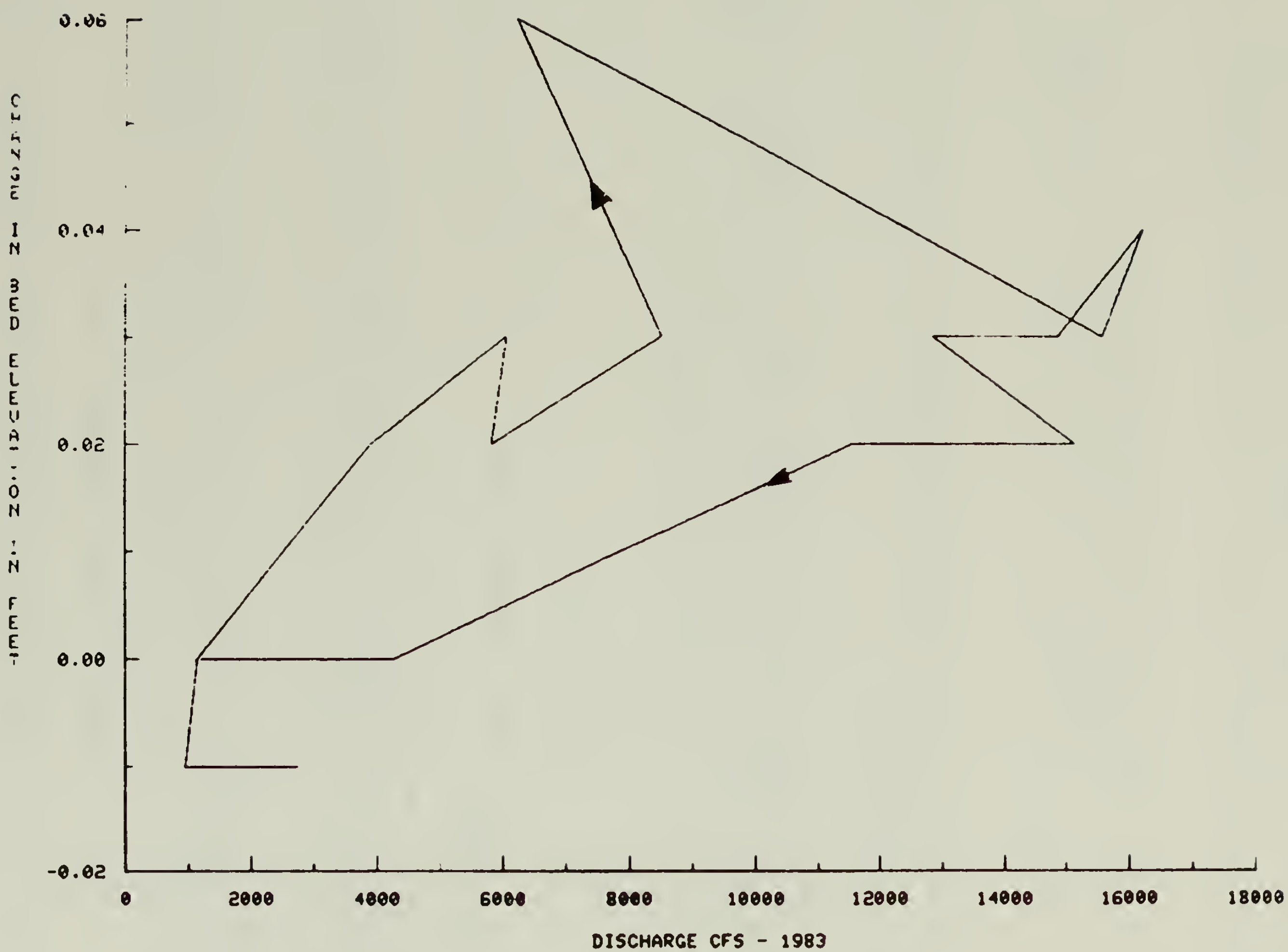
$$y_1 + \frac{\alpha_1 V_1^2}{2g} + h_e = y_2 + \frac{\alpha_2 V_2^2}{2g} \tag{2}$$

Energy headloss equation

$$h_e = LS_f + C\left(\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right) \tag{3}$$

The total sediment transport rate or bed material load is determined through the summation of the bedload and suspended load. The suspended load is calculated as a function of the bedload.

The bedload transport rate was calculated using the Meyer-Peter and Müller formula. The bedload in volume per unit of stream width is given by



AGGRADATION/DEGRADATION RIVER MILE 16.5 TO MATHERS HOLE-CROSS SECTION(MATHERS)

Figure 34.

$$q_b = \frac{12.85}{\sqrt{\rho}\ \gamma_s} (\tau - \tau_c)^{1.5} \quad (4)$$

where $$\tau_c = 0.047\ (\gamma_s - \gamma) D_s \quad (5)$$

The suspended load transport rate is computed using the Einstein method with the bedload layer as calculated from the Meyer-Peter and Müller equation as the point of known concentration. The method, using turbulent transport theory, integrates the sediment concentration profile as a function of depth. The suspended load in volume per unit of stream width is:

$$q_s = \frac{q_b}{11.6} \frac{a^{z-1}}{(1-a)^z} \left(\left(\frac{V}{U_*} + 2.5 \right) I_1 + 2.5 I_2 \right)$$

where $$z = \frac{w}{\kappa U_*}$$

The bed material load, determined by combining the suspended load and bedload are adjusted using Colby's empirical relationships for fine material concentration.

Following the calculation of the hydraulic conditions, sediment routing was accomplished on a subreach basis. The sediment transport capacity and supply is evaluated at each subreach and the sediment volume change is distributed uniformly in the reach. The sediment continuity equation employed in the calculations is

$$\frac{\partial Q_s}{\partial x} + (1-\lambda) \frac{\partial A}{\partial t} = q_L$$

where q_L is the lateral sediment inflow per unit width and is equal to zero in the model.

Armoring and bed material size distribution are evaluated in the sediment routing phase of the program. The transport capacity is determined by size fraction. If the bed shear stress does not exceed the critical shear stress, that particular size fraction will not move.

Changes in bed elevation for a given subreach is determined by sediment aggradation or degradation during a specified time interval. These changes are assumed to be uniform for the subreach represented by a single cross section. Aggradation or degradation is calculated by:

$$\Delta VOL = (\text{sediment supply} - \text{sediment transport}) \times C \times F$$

where ΔVOL is the volume of stored sediment change in the cross section, C is a conversion factor and F is a bulking factor given by F = 1/1-p where p is the bed material porosity.

The size distribution for each reach is adjusted at each time step as the particles are deposited or scoured. This adjustment reflects the change in the availability of that particular size fraction in the bed. When the specified surface layer is removed, the percentage of the each size fraction then reflects the availability from the subsurface layer. The surface and subsurface layer size distributions are specified separately at the outset of the modeling exercise. The thickness of the surface layer is also predetermined. Armoring is simulated when the eroded bed material leaves behind a layer of nontransportable particles twice the diameter of the armoring particle. Armoring may occur initially at the first time step. If the armor layer is removed, the subsurface sediment layers are again exposed with a reordered size distribution.

In the event that aggradation ensues, the percentage of fine material increases thereby reducing the large particle percentage. Conversely, degradation results in a decrease of the finer material relative to the nontransportable large sizes.

LIST OF VARIABLES

A	cross section area representing a subreach
a	depth of bed layer divided by the representative sediment diameter
C	expansion or contraction loss coefficient
D_s	representative sediment diameter
d	depth of flow
g	acceleration due to gravity
h_e	energy head loss
I_1, I_2	Einstein's integral functions
L	discharge weighted reach length
Q	water discharge
q	water specific discharge
q_L	lateral sediment inflow per unit width
q_b	bedload in volume per unit width
q_s	suspended load in volume per width
S_f	friction slope
U_*	shear velocity
V	mean flow velocity
w	particle fall velocity
y	distance above the bed
z	Rouse number
α	velocity head coefficient
γ	specific weight of water
γ_s	specific weight of sediment
κ	von Karman constant
λ	porosity of bed material
ρ	density of water
τ	bed shear stress
τ_c	critical shear stress

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environment and cultural value of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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