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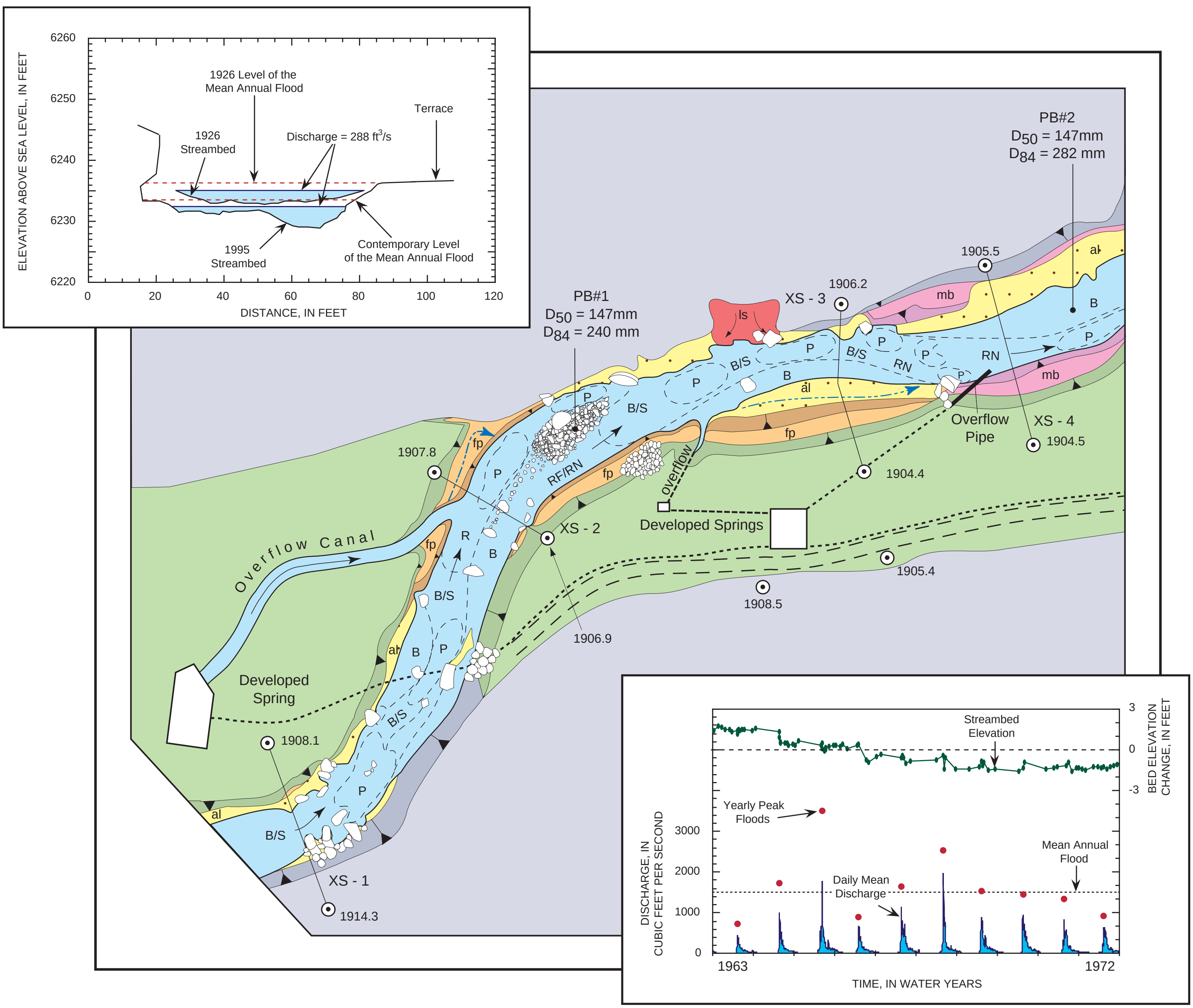
# An Assessment Methodology for Determining Historical Changes in Mountain Streams

**Mark G. Smelser**

**John C. Schmidt**



## Abstract

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Successful management of water in mountain streams by the USDA Forest Service requires that the link between resource development and channel change be documented and quantified. The characteristics of that linkage are unclear in mountain streams, and the adjustability of these streams to land-use and hydrologic change has been argued in court. One way to quantify the adjustability of a stream is to examine its geomorphic history. An excellent source of historic geomorphic data are the records associated with stream gaging stations maintained by the U.S. Geological Survey. This report describes what records are available, how to organize the data on computer spreadsheets, and discusses 6 techniques that quantify the spatial and temporal magnitude of historic channel adjustments. The discharge measurements include physical measurements of the channel. In particular, USGS discharge measurements include physical measurements of the channel. By analyzing these measurements collectively, it is possible to quantify monthly, annual, and decadal scales of adjustment. Once the history of channel adjustment is determined, it can be compared to histories of climate change, flow regulation, and land use. These comparisons may link the geomorphic adjustments to particular patterns, events, or activities. Resource managers can use this knowledge to better assess the ramifications of resource development, land use, and restoration efforts on mountain stream systems.

Keywords: gaging stations, mountain streams, historic stream channel adjustments

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# An Assessment Methodology for Determining Historical Change in Mountain Streams

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# Introduction

Water in mountain streams is one of the primary resources managed by the USDA Forest Service. One of the purposes for establishing the National Forest System was to "secure favorable conditions of water flows" (Organic Act of 1897) for downstream areas. Grazing along riparian corridors, stream regulation, and quantification of in-stream flows are some of the management issues related to securing favorable water flows. Sound policy decisions associated with these issues require that the connection between land use or stream regulation and stream channel change be understood and documented; this connection is unclear in steep, coarse-bedded mountain streams. Stream and watershed protection strategies are partly based on the assumption that land use has the potential to change the physical characteristics of streams, and that climate changes or hydrologic manipulations have the potential to alter runoff and sediment transport regimes. However, the adjustability of mountain streams to land-use, hydrologic, or sediment-transport changes has been argued in court (Gordon 1995).

While much data describes the past condition of stream channels, little research has documented the geomorphic changes along streams that drain forested mountain regions. General Land Office surveys of the late 1800s rarely extended into mountainous areas, ground-level photographs are often scarce and difficult to find, and aerial photography did not begin until the late 1930s.

This report focuses on analysis of historic records associated with stream gaging stations maintained by the U.S. Geological Survey (USGS). Stream gaging stations continuously measure the water surface elevation in a stream (figure 1) and are used to monitor and inventory the nation's surface water supply. Although these data typically only describe the condition of mountain streams over the past 50 years, they provide direct evidence of whether or not mountain streams in a particular region have adjusted to past changes in land use, hydrology, or climate.

## Mountain Stream Characteristics

The majority of mountain streams discussed in this report are fourth-order (determined from analysis of blue lines on 7.5 minute USGS quadrangle maps), coarse-bedded streams with channel gradients between 0.005 and 0.05, and $D_{84}$ values as large as 256 mm (84% of all bed material particles are less than this size). These streams typically have: 1) straight and braided channel patterns, 2) moderate width-to-depth ratios, 3) low sinuosities, 4) nearly vertical, non-cohesive banks composed of gravel and cobbles, and 5) usually flow through steep forested slopes, with occasional open parks and meandering reaches. Individual reaches resemble B3, B4, C3, C4, F3, F4, G3, and G4 types as defined by Rosgen (1994) and are classified as step-pool, plane-bed, or pool-riffle reaches as defined by Montgomery and Buffington (1993). Mountain streams are subject to highly variable discharges (Schmidt and Egenzinger 1994) and are susceptible to large sediment loads from slope failures and debris flows. In these streams, channel roughness is high, and the channel configurations are a complex mosaic of coarse sediment and in-channel obstructions such as large woody-debris.

Mountain streams typically are confined within narrow valleys, are unable to meander freely, and do not

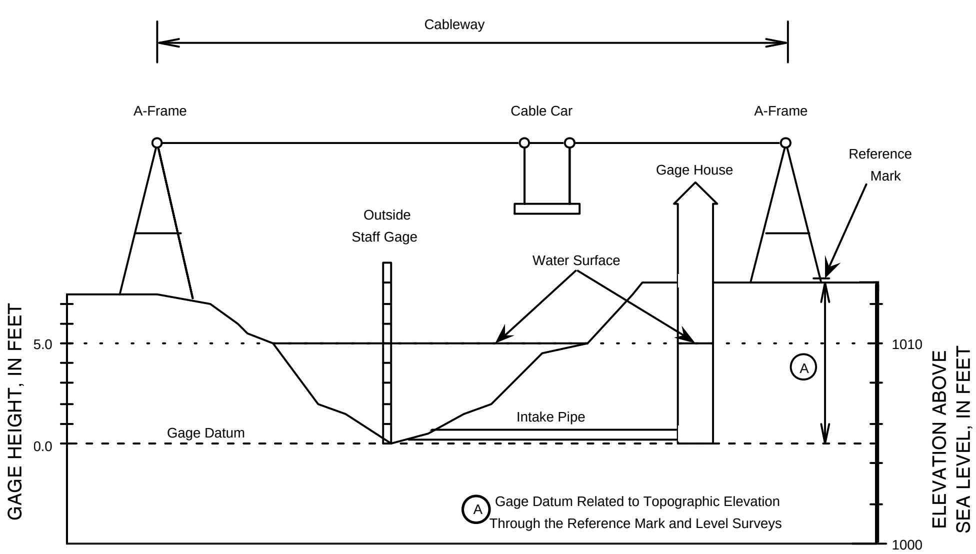



Figure 1. Schematic sketch of a typical U. S. Geological Survey stream gaging station. The cable car is used to make discharge measurements in deep stream flows. An automatic data logger inside the gage house records water-level height every 15 minutes. Reference Mark(s) are permanently mounted brass benchmarks used to control the elevation of the gage datum, which is the zero elevation point for the gage.

develop extensive floodplains. Straight and braided planforms prevail, and floodplains are small and discontinuous owing to local channel controls like bedrock outcrops, large woody debris, and other coarse debris generated by mass-wasting (Keller and Tally 1979, Andrews 1984, Lisle 1986, Grant et al. 1990, Nakamura and Swanson 1993, Andrews and Nankerveris 1995, Grant and Swanson 1995). Flood discharges that exceed bankfull in large alluvial streams flow onto floodplains where flood energy is dissipated. However, in narrow mountain valleys, flood energy remains concentrated down the axis of the valley and has the potential to modify the stream channel. Consequently, infrequent large floods with recurrence intervals between 50 and 200 years form macro-bedforms such as boulder steps in mountain streams (Grant et al. 1990, Wohl 1992, Abrahams et al. 1995, Grant and Swanson 1995). Hillslope processes like landslides, rockfalls, and debris flows are important geomorphic agents affecting mountain streams because they supply coarse sediment and woody debris to the stream, which blocks or reroutes flowing water (Grant et al. 1990, Grant and Swanson 1995, Nakamura and Swanson 1993).

Mountain streams transport a high percentage of their sediment load as bedload, and sediment transport often is used as an indicator of geomorphic change (Wolman and Miller 1960, Gordon 1995). Sediment transport in mountain streams is very difficult to quantify, and research shows that bedload transport in coarse-bedded streams is a multi-faceted process that is imperfectly understood (Parker et al. 1982, Parker and Klingeman 1982, Andrews 1983, 1984, 1994, Germanoski and Schumm 1995, Lisle 1995, Bunte 1996). Consequently, methodologies that quantify geomorphic change directly, rather than indirectly by estimating changes in reach-scale sediment mass balance, are valuable in assessing historical changes of streams.

### Method Applicability

This report explains how to analyze and interpret USGS stream gaging station records. In addition, techniques for characterizing the contemporary conditions of gaged reaches, within the context of historical analyses, are presented. This methodology is useful because:

- USGS stream gaging data may be the only historic information available for mountain streams;
- the data are quality controlled, accessible, and inexpensive to obtain; and
- compared to conventional space-for-time or paired-basin studies, these data are less expensive, quicker to analyze, and may be more site specific.

The methodology has been prepared to better understand and more efficiently manage mountain streams. These streams are key elements of the forest ecosystem and are becoming more viable as water sources.

## Previous Studies

One way to evaluate the adjustability of mountain streams is to determine whether these streams adjusted to past land-use, hydrologic, and climate changes. If this determination is possible, then future changes can be predicted with greater assurance. The documentation of historic channel change is of longstanding interest to geomorphologists. The existence of terraces, which are abandoned floodplains, along rivers throughout the world demonstrates that channels and their valleys have changed form. Bryan (1928) recognized that the deeply eroded alluvial valleys of the American Southwest had formed in the late 1800s. Determination of the timing and magnitude of change is essential to understand why these changes occurred. More recently, detailed analyses of channel change have been used to evaluate the effects of large dams (Williams and Wolman 1984), the effect of land-use practices (Trimble and Lund 1982, Wolman 1967), and flow augmentation (Dominick 1997) on stream channels.

Stream channel histories are valuable because they: 1) are a source of baseline data that can guide development, mitigation, or restoration plans; 2) provide a context to evaluate erosion and sedimentation problems related to land use and streamflow regulation; 3) reveal how natural events and human activities affect channel change; and 4) help define recovery rates and patterns. In addition, an understanding of geomorphic processes from a quantified history of the stream channel is a solid foundation for models and decisions that lead to better land and water resource management.

### Redwood Creek

Recent studies of Redwood Creek, California, illustrate the important role that a well-documented history of geomorphic change can play in affecting policy decisions for mountain forests. Redwood Creek empties into the Pacific Ocean in northern California. In 1968, the lower third of the Redwood Creek watershed, and the associated estuary, were protected within Redwood National Park, which was established to preserve groves of coastal redwood, *Sequoia sempervirens* (National Park Service 1985). The redwood groves occur on the floodplain and terraces adjacent to Redwood Creek. The Tall Trees Grove contains the first, third, and sixth tallest known trees in the world (Nolan et al. 1995). Soon after the park was established, citizens became concerned that timber harvesting outside of the park, in the upper two-thirds of the watershed, threatened the longevity of the Tall Trees Grove. Redwood Creek appeared to be widening and shallowing in response to increased runoff and sediment load from the timbered, rapidly eroding upper portion of the watershed.

In 1973, the National Park Service (NPS) and the USGS agreed to conduct detailed studies to quantify the impacts of timber harvesting and natural geomorphic processes on park resources and associated ecosystems. A key part of this research was measurement of past stream channel changes. A variety of methods were used to decipher the geomorphic history of the watershed including: 1) interpretation of time-sequential aerial photographs, 2) old land survey reviews, 3) analysis of USGS stream gaging records, 4) analysis of climate records, 5) stratigraphic analyses, 6) dendrochronology, 7) radiocarbon dating, and 8) interviews with long-time area residents. Contemporary conditions were characterized by detailed geomorphic maps and a multi-year monitoring program designed to measure erosion, transport, and sediment deposition. Results showed that the Redwood Creek watershed is one of the most rapidly eroding landscapes in the United States, and that the channel itself is highly subject to change (Janda and Nolan 1979).

Although the hypotheses about channel change originally centered on the effects of timber harvest, the detailed study revealed that climatic factors, in this case an unusually large storm, had caused much of the change along the stream. In December 1964, a large storm persisted for 12 days. The storm generated substantial flooding and caused dramatic geomorphic change in the Redwood Creek watershed (Harden 1995). Channel behavior in the 1970s and 1980s could still be related to this event (Nolan and Marron 1995). Through comparative analysis, it was determined that the storm caused more landslides and had a higher runoff than similar magnitude storms in 1953 and 1955. This suggested that the watershed had changed during the late 1950s. Additional historic analysis found that between 1947 and 1964, 67% of the watershed upstream from the park had been harvested for timber, most by clearcutting (Best 1995). Thus, the channel change due to timber harvesting had caused an increase in the vulnerability of the watershed to erosion.

Detailed studies of the Redwood Creek watershed revealed that large storms generate substantial runoff that links hillslope and channel processes together resulting in accelerated erosion. Timber harvesting appears to have increased the scale and number of such linkages. In the Redwood Creek watershed, the large 1964 storm generated landslides into the upper basin tributaries and main channel. Coincident storm-related discharges flushed the sediment out of the tributaries and into Redwood Creek, which subsequently aggraded. The aggradation caused higher water levels and the channel widened. Channel widening and higher water levels effectively eroded streambanks that supported trees and also eroded side slopes causing additional landslides. Nolan and Marron (1995) documented almost 15 ft of channel aggradation, a doubling of stream width, and a number of toppled, old-growth redwoods. Aggradation also filled inter-gravel spaces with fine sediment, effectively eliminating gravels as spawning sites. The aggradation and concomitant water level increase caused the water table to rise threatening to drown the roots of mature redwoods (Nolan and Marron 1995). Furthermore, deposition of sediment on the floodplain has the potential to bury streamside trees to such an extent as to be fatal (Janda et al. 1975).

These detailed studies of the geomorphic history and processes of the Redwood Creek watershed led to an improved understanding of the hydro-geomorphic system. That understanding was the basis for a congressional decision to expand the park in 1978 by an additional 48,000 acres of the upper watershed. Congress also designated a 30,000-acre buffer zone immediately upstream from the park within which future timber harvest plans are subject to review by the NPS.

## Others

Studies that quantify the geomorphic history of stream channels have become more common as resources have become more limited and environmental awareness has grown. McCaffery et al. (1988) examined 45 yrs of data and quantified the geomorphic history of Cottonwood Creek, California. Their purpose was to develop baseline data on channel form and migration so that the impact of 2 proposed dams could be assessed. McCaffery et al. were particularly interested in collecting data that would help evaluate the effects of reduced bed load and attenuated peak discharges on channel alignment. Simon (1994) studied approximately 35 yrs of historic data to quantify the effects of channelization on streams in west Tennessee. He developed a conceptual model of channel evolution caused by channelization and formulated equations that estimate aggradation, degradation, and channel widening. Krug and Goddard (1986) analyzed 10 yrs of historic data to assess the effects of urbanization on Pheasant Branch, Middleton, Wisconsin. They quantified erosion and sedimentation of an urbanized stream and calibrated a rainfall-runoff model for use by city planners and engineers.

Schumm and Lichtey (1963) pieced together 86 yrs of history for the Cimarron River, Kansas. They were able to determine that catastrophic floods completely obliterated the floodplain between 1914 and 1942, and that the floodplain was rebuilt within 12 yrs. In a similar study, Burkham (1972) examined 124 yrs of data on the Gila River, Arizona. He reported that catastrophic floods stripped away approximately 4 $mi^2$ of floodplain between 1905 to 1917. However, in this case, many decades were required to rebuild the floodplain. Erman (1992) examined 25 yrs of USGS gaging station data for the Little Truckee River, California, and documented changes in the hydraulic geometry. However, because of many different land-use activities in the watershed and the occurrence of a few large floods, a single cause for the channel changes was not determined. Jacobson (1995) analyzed 70 yrs of discharge measurements at 23 gages on gravel streams in the Ozark Plateau, Missouri, in an effort to correlate channel change with land use. He demonstrated the magnitude of past channel adjustments and presented reasonable causal mechanisms. James (1991, 1995) analyzed USGS discharge measurements to quantify the evolution of California streams overwhelmed by hydraulic mining sediment. Because the timing of the sediment influx was known, James was able to precisely quantify rates of channel incision, channel recovery, and sediment storage times.

## Types and Availability of Historical Data

As discussed, it is often necessary to determine whether certain types of streams have adjusted to past hydrologic or land-use changes. Geomorphic change can be directly measured, or it can be estimated by comparing the conditions of different streams within an explicit experimental design (e.g., traditional paired watershed studies). While there is no substitute for the development of a long-term, reproducible data base, such as described by Harrelson et al. (1994), there are data sets available that can be used to quantify geomorphic change. Some of the best data sets are photographs and government-sponsored surveys and investigations.

Repeat photography is an invaluable tool in reconstructing landscape change. Rogers et al. (1984) compiled and annotated an extensive bibliography of studies where investigators found the sites of previous photographs, occupied the original camera position, and made new photographs of the same scene. In this way, landscape change has been determined in many areas including some mountain landscapes. Aerial photography was first systematically used in the 1930s. These early photographs, which cover most of the Western United States, are available from the National Archives. More recent photos are available from the Eros Data Center, Sioux Falls, South Dakota, and the U.S. Department of Agriculture photo archives, Salt Lake City, Utah. Unfortunately, small stream channels in forested areas are often not visible on these photos, and it is usually impossible to detect channel change from one photo series to another.

Even older data about some regions is obtainable from General Land Office survey notes. Bryan (1928) used these data to reconstruct the timing of gully incision on the Rio Puerco River, New Mexico. Unfortunately, little of these data are available for mountain streams. Other reproducible historical data are in various administrative and technical studies by land management and conservation agencies. For instance, turn-of-the-century water development investigations may include measurements of channel cross-sections and longitudinal profiles. These studies might have been conducted by the Bureau of Reclamation, Bureau of Indian Affairs, or General Land Office. The remainder of this report focuses on the analysis of records associated with USGS stream gaging stations.

## USGS Gaging Station Data Base

The first USGS stream gaging station was established on the Rio Grande River in 1895 (Leopold 1994). Today there are over 7,500 gaging stations in operation around the United States and over 3,000 discontinued stations (Leopold 1994, Leopold et al. 1964). The USGS operates stream gages as part of the gaging station network that monitors the nation's water supply and also for the collection of baseline data required for the design or operation of specific water projects (Rantz et al. 1982). Gaging stations continuously measure water-surface elevation in a channel. Approximately once a month, discharge measurements are made at the gage station to quantify the rating relation between the water-surface level and the rate of water flow in the stream. Each year the data collected at every station are summarized and published.

### Location Criteria

Although the analysis of gaging data is a powerful technique for evaluating historical channel change, there are unavoidable limitations. Gaging stations are not randomly distributed and are typically located along the periphery of mountains. Thus, data that describes channel change in the interior parts of some mountain ranges may be limited. The specific location of each gage is based on where it most accurately will measure the water surface elevation for long time periods. Consequently, the stations are established at sites that provide the best combination of accessibility, measurement accuracy, and long-term channel stability. Rantz et al. (1982) lists the following criteria as ideal for a gaging station site.

- The stream is straight for about 300 ft up and downstream from the gage site.
- Stream flow is confined to one channel at all stages, and no flow bypasses the site as subsurface flow.
- The streambed is not subject to scour and fill and is free of aquatic growth.
- Banks are permanent, high enough to contain most floods, and free of brush.
- Unchanging natural controls are present for both low and high flows.
- A pool is present upstream from the control to ensure a recording at extremely low flow and to avoid high velocities at the intakes during periods of high flow.
- The gage site is far enough upstream from the confluence with another stream to avoid any influence that the another stream may have on the stage at the gage site.
- A satisfactory reach for measuring discharge at all stages is available within reasonable proximity of the gage site.
- The site is readily accessible for ease in installation and operation of the gaging station.

Although gaging stations are located along reaches that are relatively stable, Rantz et al. (1982) acknowledged that "all streams in a given region may have unstable beds and banks" and sometimes "a poor site must be accepted." Thus, when quantifying geomorphic change at a gage site, it is important to recognize that these sites may be more stable than other parts of the same stream, but they are not static or immune to change.

## Records and Accessibility

For each USGS gage station, information is recorded in 7 different files. All of the files except the recorder tapes are used to some degree in the historical analysis.

### *1. Miscellaneous Working Files*

These are files containing correspondence and calculations regarding gage establishment and discontinuance, corrections to the rating relation, and miscellaneous information. This file may include a Station Description Sheet and rarely includes photographs. While a gage is in active operation, these data are stored at State District headquarters. After a gage is discontinued, these files may be archived.

### *2. Discharge Measurements*

These are the actual discharge measurements made by the hydrographers in the field. These measurements are made approximately once a month and are recorded on a 8 x 5 inch, multi-page form (Form 9-275). These records make up most of the subsequent historical analyses and contain measurements of channel width, depth, flow velocity, and a measured cross-section. While a gage is in active operation, this data set is typically maintained in its entirety and stored at State District headquarters. After a gage is discontinued, these files may be archived. The data from these Discharge Measurements are summarized on Form 9-207, which is also available from the State District headquarters.

### *3. Level Notes*

These are surveyed elevation measurements of the gage datum and gage Reference Marks. These measurements are performed periodically to confirm that the gage and datum have not changed due to ground subsidence, flood damage, or frost heaving. These measurements are also recorded on a 8 x 5 inch form (Form 9-276). Typically, these data are maintained with the Discharge Measurements.

### *4. Recorder Tapes*

These are 4-inch wide rolls of paper tape that were punched by the mechanical water-level recorder in the gage house. These data are not used in historical analyses.

### *5. Station Analysis Reports*

These are annual, unpublished reports that describe all of the activities at the gage for a given year. These reports typically include the Station Description Sheet, annual hydrograph, rating relation, and occasionally photographs. These data are stored at the State District headquarters and are periodically archived even while the gage is in operation.

### *6. USGS Water-Data Reports*

These are the annual reports published by the USGS that summarize the water data collected by the USGS on an individual state basis. Before 1975, this information was published in a series of USGS water-supply papers entitled *Surface Water Supply of the United States*. Both the Water-Data Reports and Water-Supply Papers are in many libraries. Recent copies of the Water-Data Reports are available for purchase from State District offices. The summary information is also available on CD-ROM and the Internet.

### *7. Statistical Analyses of Discharge Data*

The USGS statistically analyzes the discharge data for each gage station. These data are used to compute flow duration curves, flood frequency, and low-flow frequency statistics. This collection is known as the Daily Values Statistical Program (DVSTAT) data base.

Because of differences in use, size, and volume, the files and records listed above are not stored together while a gage is in operation. Additionally, because of space limitations, some of these files are periodically archived. As a result, parts of the record for a particular gage are located at the State District headquarters, while others are at the USGS archives. Archived data can only be accessed by USGS personnel.

# Data Compilation — Historic Records

## Gage Station Selection

Although Forest Service hydrologists may be aware of the existence of most active gage stations, additional data concerning channel change exist at gaging station sites that have been discontinued. For example, there are only 40 active stream gages in the Uinta Mountains of eastern Utah, but there are 90 other sites where gaging took place in the past (figure 2). The introductory text of the annual water data reports typically includes a list of the discontinued gage stations, and these data are also available on the Internet. The exact location of these sites can be determined from the annual water data reports that were published while the gage was active.

Since the goal of most forest hydrologists is to understand the characteristics of regional channel change and the specific history of a few sites, investigations typically are undertaken at a number of sites. Long-term stations whose point of measurement has not moved and whose bed and banks are adjustable, are the most desirable study sites. Short-term sites may be useful if they were installed before some land management activity that is of concern. Discontinued sites may provide valuable data if the site and its reference marks can be found. Even though the record of intervening years may be unknown, channel change at the multi-decade scale can be evaluated. Once the gage(s) are selected for detailed analysis, all published information describing the gage's history should be recorded. This information is necessary to make efficient requests for information from the USGS.

## Gage Record Requests

The first request to the USGS is for 2 types of information about each gage station. The first is the Station Description Sheet that succinctly describes how to find the gage, the Reference Marks that define the gage datum, and the history of gage datum changes. It is essential to know whether or not the gage station has moved or if any datum changes have occurred. Gage stations are occasionally relocated due to wash-outs, channel pattern changes, accessibility, and better measurement potential. It is important to realize that, over the period of record, data reported for a specific gage station may have been collected at a number of different locations along the stream. Similarly, gage datums are changed to accommodate streambed changes or modifications to the gage house.

The second type of information concerns how many rating relations have been developed for the particular gage. The existence of multiple rating curves for one gage suggests that the streambed elevation has changed over time. For active gages, the Station Description Sheet and rating relation information are accessible at district headquarters. This information for discontinued gages may be similarly accessible, but may also have been archived. The retrieval of archived records requires that USGS personnel research accession numbers of archived data and make formal requisitions to the archives. Upon receipt of the written requisition, the archivist locates the records and ships them to the USGS District Office. This process requires a minimum of 2 weeks. It is important to remember that all of the records for one gage are not archived together, and that the USGS does not have personnel available to review the retrieved records for completeness.

Once a gage station is selected for detailed analysis, it is necessary to request the Discharge Measurements (DMs) and Level Notes (figures 3 and 4) for that station. As before, these records will be readily available for active gages but may have been archived if the station was discontinued. These records are entered into computer spreadsheets and analyzed in detail. The USGS will not release the original records to the public; work must be done at the USGS, which requires a laptop computer, or the records must be photocopied. If the records are photo-

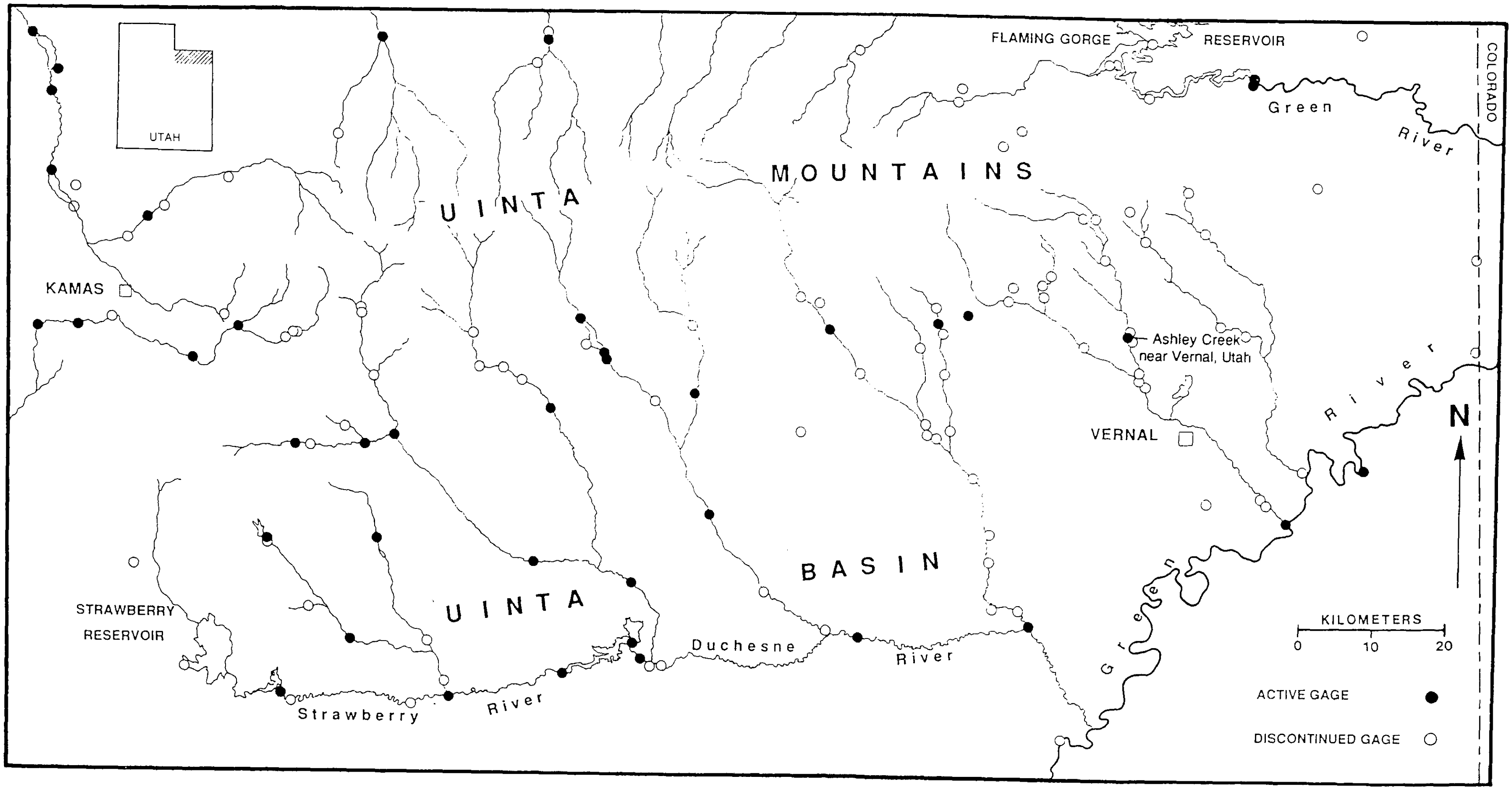



Figure 2. Map of northeastern Utah and the Uinta Mountains showing active and discontinued U. S. Geological Survey stream gaging stations.

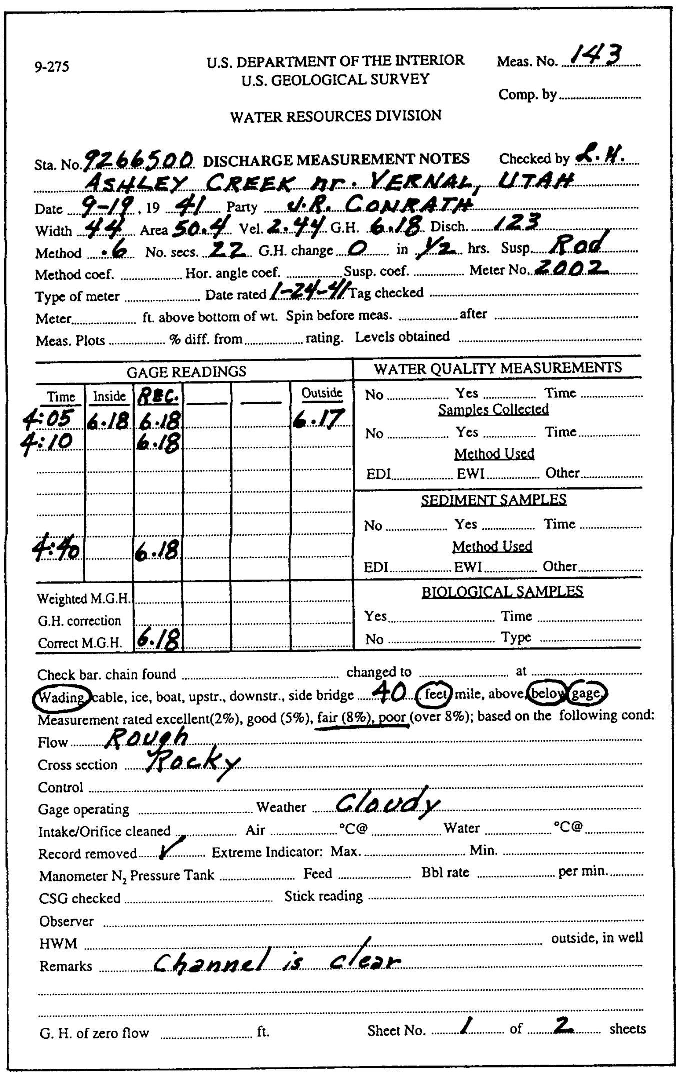
copied, care must be taken because they are fragile and irreplaceable.

Although photocopying the records is an expense, it is desirable because the records are then owned, and they can be immediately referenced if errors in data entry are suspected. Ease of cross-section analysis is a second benefit to owning the records. During the data entry phase of compilation, it is impossible to know which DMs will be used in the cross-section analysis. Additionally, since so few DMs are used for this purpose, it is inefficient and unnecessary to enter the cross-section measurement from each DM into the computer. If the records are not owned, a second request to the USGS for the records is required to analyze specific cross-sections.

## Discharge Measurement Data Entry

The basic data used in quantitative analysis of channel change are the DMs. Analysis of this large data set is best conducted using computer spreadsheet software and statistical graphing software. The spreadsheet used for data entry should include the following column or field headings.

1. Record number
2. Date (actual date)
3. Julian day (days since 1/1/1900)
4. Month



9-275 U.S. DEPARTMENT OF THE INTERIOR Meas. No. 143
U.S. GEOLOGICAL SURVEY Comp. by
WATER RESOURCES DIVISION

Sta. No. 9266500 DISCHARGE MEASUREMENT NOTES Checked by L.H.
ASHLEY CREEK nr. VERNAL, UTAH
Date 9-19, 19 41 Party J.R. CONRATH
Width 44 Area 50.4 Vel. 2.44 G.H. 6.18 Disch. 123
Method .6 No. secs. 22 G.H. change 0 in 1/2 hrs. Susp. Rod
Method coef. Hor. angle coef. Susp. coef. Meter No. 2002
Type of meter Date rated 1-24-41 Tag checked
Meter ft. above bottom of wt. Spin before meas. after
Meas. Plots % diff. from rating. Levels obtained

GAGE READINGS

| Time | Inside | REC. | | | Outside |
|---|---|---|---|---|---|
| 4:05 | 6.18 | 6.18 | | | 6.17 |
| 4:10 | | 6.18 | | | |
| | | | | | |
| | | | | | |
| 4:40 | | 6.18 | | | |

Weighted M.G.H.
G.H. correction
Correct M.G.H. 6.18

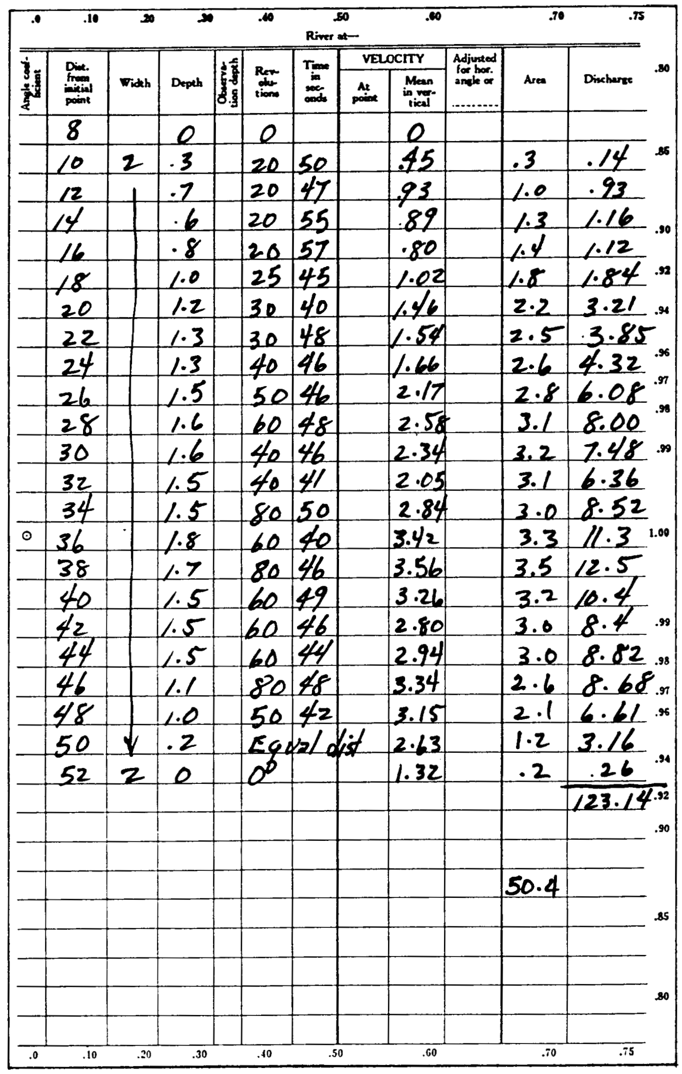
WATER QUALITY MEASUREMENTS
No Yes Time
Samples Collected
No Yes Time
Method Used
EDI EWI Other

SEDIMENT SAMPLES
No Yes Time
Method Used
EDI EWI Other

BIOLOGICAL SAMPLES
Yes Time
No Type

Check bar. chain found changed to at
Wading, cable, ice, boat, upstr., downstr., side bridge 40 feet, mile, above, below gage
Measurement rated excellent(2%), good (5%), fair (8%), poor (over 8%); based on the following cond:
Flow Rough
Cross section Rocky
Control
Gage operating Weather Cloudy
Intake/Orifice cleaned Air °C@ Water °C@
Record removed ✓ Extreme Indicator: Max. Min.
Manometer $N_2$ Pressure Tank Feed Bbl rate per min.
CSG checked Stick reading
Observer
HWM outside, in well
Remarks Channel is clear

G. H. of zero flow ft. Sheet No. 1 of 2 sheets



River at—

| Angle coefficient | Dist. from initial point | Width | Depth | Observation depth | Revolutions | Time in seconds | Velocity: At point | Velocity: Mean in vertical | Adjusted for hor. angle or | Area | Discharge |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 8 | | 0 | | 0 | | | 0 | | | |
| | 10 | 2 | .3 | | 20 | 50 | | .45 | | .3 | .14 |
| | 12 | | .7 | | 20 | 47 | | .93 | | 1.0 | .93 |
| | 14 | | .6 | | 20 | 55 | | .89 | | 1.3 | 1.16 |
| | 16 | | .8 | | 20 | 57 | | .80 | | 1.4 | 1.12 |
| | 18 | | 1.0 | | 25 | 45 | | 1.02 | | 1.8 | 1.84 |
| | 20 | | 1.2 | | 30 | 40 | | 1.46 | | 2.2 | 3.21 |
| | 22 | | 1.3 | | 30 | 48 | | 1.54 | | 2.5 | 3.85 |
| | 24 | | 1.3 | | 40 | 46 | | 1.66 | | 2.6 | 4.32 |
| | 26 | | 1.5 | | 50 | 46 | | 2.17 | | 2.8 | 6.08 |
| | 28 | | 1.6 | | 60 | 48 | | 2.58 | | 3.1 | 8.00 |
| | 30 | | 1.6 | | 40 | 46 | | 2.34 | | 3.2 | 7.48 |
| | 32 | | 1.5 | | 40 | 41 | | 2.05 | | 3.1 | 6.36 |
| | 34 | | 1.5 | | 80 | 50 | | 2.84 | | 3.0 | 8.52 |
| ⊙ | 36 | | 1.8 | | 60 | 40 | | 3.42 | | 3.3 | 11.3 |
| | 38 | | 1.7 | | 80 | 46 | | 3.56 | | 3.5 | 12.5 |
| | 40 | | 1.5 | | 60 | 49 | | 3.26 | | 3.2 | 10.4 |
| | 42 | | 1.5 | | 60 | 46 | | 2.80 | | 3.0 | 8.4 |
| | 44 | | 1.5 | | 60 | 44 | | 2.94 | | 3.0 | 8.82 |
| | 46 | | 1.1 | | 80 | 48 | | 3.34 | | 2.6 | 8.68 |
| | 48 | | 1.0 | | 50 | 42 | | 3.15 | | 2.1 | 6.61 |
| | 50 | ↓ | .2 | | Equal dist | | | 2.63 | | 1.2 | 3.16 |
| | 52 | 2 | 0 | | 0 | | | 1.32 | | .2 | .26 |
| | | | | | | | | | | | 123.14 |
| | | | | | | | | | | 50.4 | |

Figure 3. Example of a U. S. Geological Survey Discharge Measurement. This measurement was made at Ashley Creek on September 9, 1941. The first page contains a data summary, notes concerning channel conditions, and measurement location. The second page contains the measured cross-section and discharge calculations. A maximum depth of 1.8 ft was recorded 36 ft from the initial point.

5. Width
6. Area
7. Gage height
8. Mean velocity
9. Discharge
10. Maximum depth
11. Measurement location
12. Notes

All of the data for these fields, except maximum depth, is on the first page of each DM (figure 3). As mentioned, this information is also available on Form 9-207. Maximum depth, the deepest part of the channel recorded during the measurement, is only found on the second page of the DM (figure 3). Maximum depth is not listed on Form 9-207. Measurement location is where the DM was made relative to the gage. This location is typically estimated, and terms like "1/4 mile above," "50 ft below cableway," and "at gage" are recorded in the DM. The DM location is an important parameter used to sort the spreadsheet data. Thus, numbers not phrases should be used in this spreadsheet field. Since the gage is the reference location, its location is recorded as zero in the spreadsheet. Measurement locations upstream from the gage are entered as positive numbers in the spreadsheet, and measurement locations downstream from the gage are entered as negative numbers.

The Notes field in the spreadsheet is for any noteworthy information recorded on the DM. For example, winter measurements often note that ice affects the gage and stream channel. DMs made under ice commonly occur as significant outliers in plots of hydraulic geometry and should not be used in historical analyses. Therefore, it is important to be able to sort out these measurements from the basic data set for selected analyses. It is recommended that a set of simple abbreviations be developed that impart the message of the notes and allow for systematic sorting of this field. As the analysis proceeds, it is necessary to sort the data by additional spreadsheet columns related to time and data calculations. Table 1 is an example of a computer spreadsheet with all data fields.

9-276

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES DIVISION

Station Number 9266500

LEVEL NOTES

Stream Ashley Creek nr. Vernal
Locality
Party Webb & Kennington Date 7-16, 1965

| STATION | B. S. | HT. INST. | F. S. | ELEVATION | REMARKS |
|---|---|---|---|---|---|
| Lowered well, lowered staff gage on well, changed control. Well is at same location. | | | | | |
| I.G. | 12.54 | | | 0.00 | 0.0 on I.G. |
| | | 12.54 | | | |
| | | | 12.25 | 0.29 | lower intake, inside |
| | | | 11.18 | 1.36 | upper intake, inside |
| | | | 12.24 | 0.30 | lower intake, outside |
| | | | 11.20 | 1.34 | upper intake, outside |
| | | | 12.53 | 0.01 | 0.0 on O.G. |
| | | | 10.98 | 1.56 | W.S., inside well |
| | Brass cap | | 12.53 | 0.01 | |
| R.M.#1 | in Rock | | 0.10 | 12.44 | new datum after well lowered |
| | | | | | |
| T.P. 1 | 10.76 | | 10.83 | 1.71 | |
| | | 12.47 | | | |
| R.M.#1 | | | 0.03 | 12.44 | |
| I.G. | | | 12.47 | 0.00 | 0.00 on Gage |
| Error of closure 0.00 | | | | | |
| New datum 1.291 lower | | | | | |

No. 2 of 2 sheets Comp. by RW Chk. by

Figure 4. Example of U. S. Geological Survey Level Notes. These notes describe a datum change on Ashley Creek. The gage datum was lowered 1. 291 ft on July 16, 1965.

## Data Analysis — Historic Records

The following set of analytical techniques quantifies stream channel change through time. A basic understanding of fluvial geomorphology is necessary. This set of analyses is not exhaustive; it is anticipated that specific needs and personal creativity will lead to other avenues of analysis. The techniques are presented in a sequential manner beginning with the analysis of the rating relation. Later sections examine changes in width, depth, and hydraulic geometry. Lastly, geomorphic change is linked to discharge. In the ensuing discussion, the mean annual flood (arithmetic average of all annual peak floods for the period of record) is used as a reference discharge because it has a recurrence interval of 2.3 years, and floods with recurrence intervals between 1.5 and 3 yrs are responsible for the formation and maintenance of large alluvial streams (Leopold 1994). Recurrence intervals are determined from flood frequency curves (figure 5) that rank the magnitudes of the annual peak discharges for each year of record.

Table 1. Example of a computer spreadsheet with all data fields used to organize the data from the U. S. Geological Survey Discharge Measurements.

| Record number | Date | Julian day since 1/1/1900 | Month | Water year | Width w (ft) | Area A ($ft^2$) | Mean velocity v (ft/sec) | Gage height GH (ft) | Discharge Q ($ft^3$/sec) | Maximum depth MXDPTH (ft) | Mean depth MNDPTH (ft) | Measure-ment location from gage (ft) | Correction factor COFAC (ft) | Rectified gage height RGH (ft) | Water surface elevation WSE (ft) | Mean streambed elevation MSBE (ft) | Minimum streambed elevation MINSBE (ft) | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19 | 11/14/17 | 6528 | 11 | 18 | 29 | 23.3 | 3.01 | 3.56 | 70.2 | 1.3 | 0.8 | 50 | -1.959 | 1.60 | 6232.60 | 6231.8 | 6231.3 | |
| 20 | 02/15/18 | 6621 | 2 | 18 | 19 | 20.4 | 1.70 | 3.44 | 34.7 | 1.5 | 1.1 | 1000 | -1.959 | 1.48 | 6232.48 | 6231.4 | 6231.0 | |
| 21 | 04/21/18 | 6686 | 4 | 18 | 31 | 22.0 | 1.63 | 3.46 | 35.9 | 1.1 | 0.7 | 100 | -1.959 | 1.50 | 6232.50 | 6231.8 | 6231.4 | |
| 23 | 08/4/18 | 6791 | 8 | 18 | 36 | 40.0 | 2.44 | 3.66 | 97.6 | 1.9 | 1.1 | 50 | -1.959 | 1.70 | 6232.70 | 6231.6 | 6230.8 | |
| 24 | 11/5/18 | 6884 | 11 | 19 | 32 | 31.6 | 2.04 | 3.55 | 64.5 | 1.4 | 1.0 | 100 | -1.959 | 1.59 | 6232.59 | 6231.6 | 6231.2 | |
| 25 | 01/22/19 | 6962 | 1 | 19 | 28 | 23.4 | 1.36 | 3.34 | 31.9 | 1.3 | 0.8 | 50 | -1.959 | 1.38 | 6232.38 | 6231.5 | 6231.1 | |
| 26 | 05/12/19 | 7072 | 5 | 19 | 43 | 55.3 | 3.62 | 3.97 | 200.0 | 2.0 | 1.3 | 100 | -1.959 | 2.01 | 6233.01 | 6231.7 | 6231.0 | |
| 27 | 09/25/19 | 7208 | 9 | 19 | 28 | 26.8 | 1.99 | 3.49 | 53.3 | 1.4 | 1.0 | 100 | -1.959 | 1.53 | 6232.53 | 6231.6 | 6231.1 | |
| 28 | 03/17/20 | 7382 | 3 | 20 | 29 | 20.5 | 1.40 | 3.38 | 28.4 | 1.1 | 0.7 | | -1.959 | 1.42 | 6232.42 | 6231.7 | 6231.3 | |
| 29 | 05/27/20 | 7453 | 5 | 20 | 72 | 166.0 | 5.69 | 6.08 | 945.0 | 3.2 | 2.3 | -100 | -1.959 | 4.12 | 6235.12 | 6232.8 | 6231.9 | |
| 30 | 05/28/20 | 7454 | 5 | 20 | 77 | 151.0 | 5.67 | 6.10 | 856.0 | 3.8 | 2.0 | | -1.959 | 4.14 | 6235.14 | 6233.2 | 6231.3 | |
| 31 | 10/29/20 | 7608 | 10 | 21 | 40 | 36.1 | 1.51 | 4.38 | 54.6 | 1.3 | 0.9 | 10 | -1.959 | 2.42 | 6233.42 | 6232.5 | 6232.1 | |
| 32 | 03/27/21 | 7757 | 3 | 21 | 49 | 35.4 | 0.97 | 4.20 | 34.2 | 1.1 | 0.7 | 4 | -1.959 | 2.24 | 6233.24 | 6232.5 | 6232.1 | |
| 33 | 07/1/21 | 7853 | 7 | 21 | 55 | 70.5 | 3.60 | 5.25 | 254.0 | 2.1 | 1.3 | -75 | -1.959 | 3.29 | 6234.29 | 6233.0 | 6232.2 | |
| 34 | 07/27/21 | 7879 | 7 | 21 | 45 | 52.4 | 2.36 | 4.86 | 124.0 | 1.8 | 1.2 | 0 | -1.959 | 2.90 | 6233.90 | 6232.7 | 6232.1 | |
| 35 | 10/7/21 | 7951 | 10 | 22 | 41 | 37.4 | 2.43 | 4.74 | 91.0 | 1.7 | 0.9 | -100 | -1.959 | 2.78 | 6233.78 | 6232.9 | 6232.1 | |
| 36 | 01/23/22 | 8059 | 1 | 22 | 26 | 25.4 | 1.62 | 4.43 | 41.2 | 2.0 | 1.0 | 400 | -1.959 | 2.47 | 6233.47 | 6232.5 | 6231.5 | |
| 37 | 06/4/22 | 8191 | 6 | 22 | 80 | 155.4 | 6.62 | 7.55 | 1030.0 | 3.6 | 1.9 | 100 | -1.959 | 5.59 | 6236.59 | 6234.6 | 6233.0 | |
| 38 | 06/17/22 | 8204 | 6 | 22 | 126 | 147.0 | 4.82 | 7.96 | 700.0 | 2.3 | 1.2 | -100 | -1.959 | 6.00 | 6237.00 | 6235.8 | 6234.7 | |
| 39 | 09/5/22 | 8284 | 9 | 22 | 44 | 44.9 | 2.38 | 6.35 | 107.0 | 2.0 | 1.0 | | -1.959 | 4.39 | 6235.39 | 6234.4 | 6233.4 | |
| 40 | 03/25/23 | 8485 | 3 | 23 | 24 | 26.0 | 1.33 | 5.85 | 34.5 | 2.0 | 1.1 | 150 | -1.959 | 3.89 | 6234.89 | 6233.8 | 6232.9 | |
| 41 | 06/10/23 | 8562 | 6 | 23 | 71 | 131.0 | 4.53 | 7.48 | 594.0 | 2.9 | 1.8 | 50 | -1.959 | 5.52 | 6236.52 | 6234.7 | 6233.6 | |
| 42 | 06/24/23 | 8576 | 6 | 23 | 52 | 76.1 | 3.76 | 6.88 | 286.0 | 2.4 | 1.5 | 20 | -1.959 | 4.92 | 6235.92 | 6234.5 | 6233.5 | |
| 43 | 07/6/23 | 8588 | 7 | 23 | 51 | 58.9 | 3.02 | 6.62 | 208.0 | 2.1 | 1.4 | 20 | -1.959 | 4.66 | 6235.66 | 6234.3 | 6233.6 | |
| 44 | 07/18/23 | 8600 | 7 | 23 | 48 | 58.5 | 2.80 | 6.44 | 164.0 | 1.9 | 1.2 | 20 | -1.959 | 4.48 | 6235.48 | 6234.3 | 6233.6 | |
| 45 | 05/12/24 | 8899 | 5 | 24 | 59 | 106.0 | 3.99 | 7.33 | 423.0 | 2.5 | 1.8 | 30 | -1.959 | 5.37 | 6236.37 | 6234.6 | 6233.9 | |
| 46 | 09/20/24 | 9030 | 9 | 24 | | | | 5.94 | 41.5 | | | | -1.959 | 3.98 | 6234.98 | 6235.0 | | |
| 47 | 01/26/25 | 9158 | 1 | 25 | 23 | 23.3 | 1.34 | 5.81 | 31.1 | 1.3 | 1.0 | 3000 | -1.959 | 3.85 | 6234.85 | 6233.8 | 6233.6 | |
| 48 | 04/25/25 | 9247 | 4 | 25 | 43 | 39.1 | 1.54 | 6.03 | 60.4 | 1.3 | 0.9 | 31 | -1.959 | 4.07 | 6235.07 | 6234.2 | 6233.8 | |
| 49 | 05/25/25 | 9277 | 5 | 25 | 48 | 66.0 | 3.14 | 6.63 | 207.0 | 1.9 | 1.4 | | -1.959 | 4.67 | 6235.67 | 6234.3 | 6233.8 | |
| 50 | 08/14/25 | 9358 | 8 | 25 | 45 | 42.6 | 1.81 | 6.13 | 77.0 | 1.2 | 0.9 | | -1.959 | 4.17 | 6235.17 | 6234.2 | 6234.0 | |
| 51 | 12/6/25 | 9472 | 12 | 26 | 44 | 38.0 | 1.47 | 6.04 | 55.8 | 1.2 | 0.9 | 25 | -1.959 | 4.08 | 6235.08 | 6234.2 | 6233.9 | |
| 52 | 05/2/26 | 9619 | 5 | 26 | 55 | 82.8 | 3.48 | 7.00 | 288.0 | 2.2 | 1.5 | 25 | -1.959 | 5.04 | 6236.04 | 6234.5 | 6233.8 | |
| 54 | 06/27/26 | 9675 | 6 | 26 | 46 | 49.2 | 2.08 | 6.28 | 103.0 | 1.4 | 1.1 | 20 | -1.959 | 4.32 | 6235.32 | 6234.2 | 6233.9 | |
| 56 | 08/30/26 | 9739 | 8 | 26 | 44 | 39.4 | 1.51 | 6.06 | 69.6 | 1.2 | 1.0 | 20 | -1.959 | 4.10 | 6235.10 | 6234.1 | 6233.9 | |
| 57 | 10/23/26 | 9793 | 10 | 27 | 42 | 30.4 | 1.26 | 5.93 | 39.2 | 1.0 | 0.7 | 10 | -1.959 | 3.97 | 6234.97 | 6234.2 | 6234.0 | |
| 59 | 02/8/27 | 9901 | 2 | 27 | 14 | 11.8 | 2.39 | 5.83 | 28.2 | 1.4 | 0.8 | 1000 | -1.959 | 3.87 | 6234.87 | 6234.0 | 6233.5 | |
| 60 | 5/29/27 | 10011 | 5 | 27 | 52 | 82.0 | 3.45 | 6.99 | 283.0 | 2.4 | 1.6 | | -1.959 | 5.03 | 6236.03 | 6234.5 | 6233.6 | |

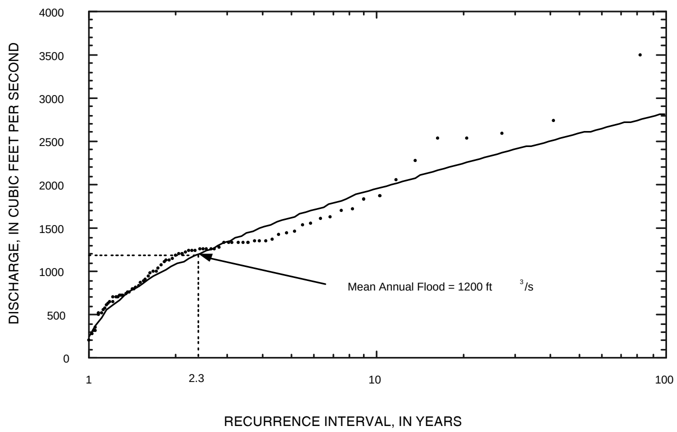



Figure 5. Flood Recurrence Interval Curve for Ashley Creek. This is a Log Pearson Type III curve using all 83 years of flood data. The mean annual flood of 1200 ft$^3$/sec plots at a recurrence interval of 2.3 years.

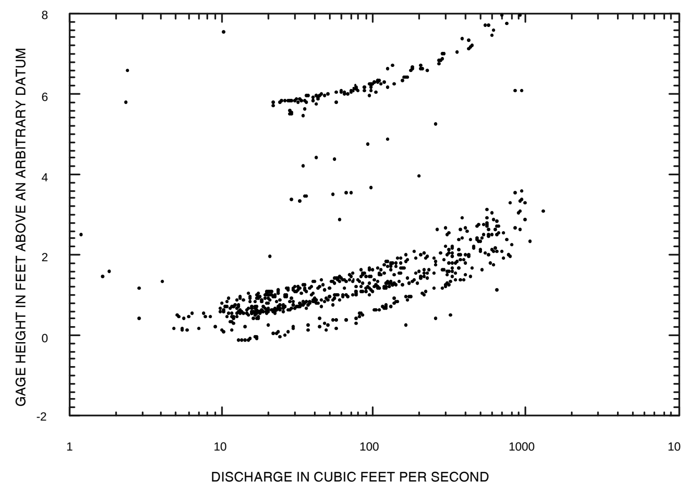



Figure 6. Rating Relation for Ashley Creek. This plot was generated using all gage heights as recorded on the original Discharge Measurements. There are numerous lineations that occur over a large range of about 8 ft. This plot indicates that either the gage datum, streambed, or both have changed substantially through time.

## Rating Curve

The first step in recognizing geomorphic change is to analyze the rating relation. The rating relation, also known as the stage-discharge relation, is a graph that depicts the relation between measured stream discharges and water surface elevations measured at the same time by the stream gage. The premise of this analysis is that if the gage datum and streambed elevation remain constant through time, then a given discharge should always correspond to the same gage height. However, if a given discharge is correlated with different gage heights over time, then either the gage datum or the streambed elevation has changed. Figure 6 is a plot of the rating relation for Ashley Creek, Utah, using all of the gage heights as recorded on the DMs (i.e., no corrections have been made for gage datum changes). Ashley Creek is an unregulated stream that has been continuously gaged since 1917. As evidenced by the wide scatter of data, figure 6 suggests substantial adjustability over the period of record, which could be the result of aggradation, degradation, or gage datum changes. To remove anomalous trends caused by datum changes, it is necessary to rectify the recorded gage heights to a common datum; the most logical choice is to adjust all historic data to the present-day gage datum.

Rectification of gage heights requires all information on datum changes through the period of record. This information is in the Station Description Sheet, the Level Notes, and the Station Analysis Reports. With this information, it is possible to calculate the correction factors that will rectify historic gage heights to the contemporary gage datum. The correction factor (COFAC) is calculated by:

$$\text{COFAC} = \text{ECGD} - \text{EHGD} \qquad (1)$$

where ECGD is the topographic elevation of the contemporary gage datum and EHGD is the topographic elevation of a historic gage datum. When numerous datum changes have occurred, the calculations can be confusing and it is useful to construct a graph of the datum changes through time (figure 7). The sketch in figure 7 shows specific corrections for particular time periods. These time-specific corrections are applied to the recorded gage heights by adding 2 new fields to the spreadsheet. One is the correction factor (COFAC) and the second is the rectified gage height (RGH) where:

$$\text{RGH} = \text{Gage Height} + \text{COFAC} \qquad (2)$$

It is advisable to create another column in the spreadsheet that equates the RGH to a topographic elevation. This column is referred to as water surface elevation (WSE) and:

$$\text{WSE} = \text{Topographic Elevation of the Contemporary Gage Datum} + \text{RGH} \qquad (3).$$

The topographic elevation of the gage datum is determined through the Reference Marks and USGS 7.5 minute topographic maps. Once all the discharge measurements are rectified, a new plot of the rating relation is generated (figure 8). For Ashley Creek, the plot still shows substantial variability but not as much as the unrectified plot of

Figure 7. The history of gage datum changes at the Ashley Creek gaging station. This graph shows the history of datum changes relative to the 1996 gage datum. The correction factor (COFAC) is the value that will rectify an old water surface elevation to the contemporary gage datum using: Gage Height + COFAC = Rectified Gage Height (RGH). For example, a water surface elevation of 1.959 ft in 1920 would equal, 1.959 ft + (-1.959 ft) = 0.0 ft on the contemporary gage. From the Level Notes and Station Analysis Reports:

1=10/1/42-Gage datum raised 5 ft
2=8/5/60-Gage datum lowered 0.66 ft
3=7/16/65-Gage datum lowered 1.291 ft
4=7/30/68-Gage datum lowered 0.09 ft
5=8/86-Gage datum lowered 1.00 ft

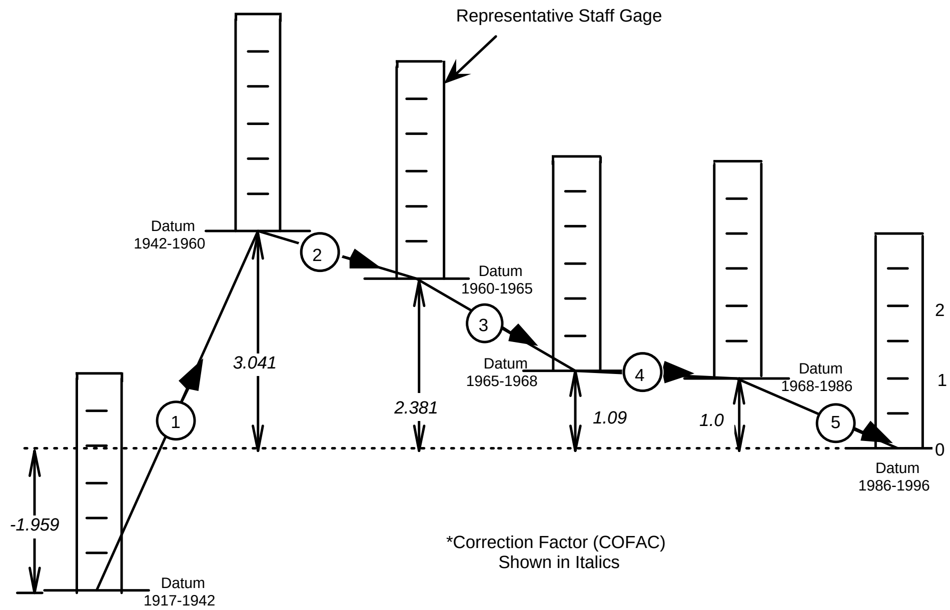



figure 6. Because the gage heights have all been rectified, the adjustments are due to changes in the streambed elevation.

## Streambed Elevation

The rectified rating relation (figure 8) shows that the streambed at the gage has adjusted through time. However, temporal trends and spatial magnitudes are not discernible from the rating relation. Such trends and magnitudes can be illustrated and measured by plotting the mean streambed elevation through time. For each DM, a mean depth can be calculated using the continuity equation:

$$Q = Av \quad (4)$$

where Q is discharge, A is cross-sectional area, and v is velocity. A mean depth (MNDPTH) value is calculated in the spreadsheet with:

$$MNDPTH = Q/wv \quad (5)$$

where w is the channel top width. It is important to realize that mean depth is a calculated value and not a field measurement. The subtraction of MNDPTH from the water surface elevation (WSE) gives the mean streambed elevation (MSBE):

$$MSBE = WSE - MNDPTH \quad (6)$$

This relation is illustrated in figure 9. A similar calculation is that which returns the minimum streambed elevation. The minimum streambed elevation (MINSBE) is also known as the thalweg elevation and is calculated by substituting maximum (MXDPTH) for MNDPTH in equation (6).

$$MINSBE = WSE - MXDPTH \quad (7)$$

Note that MXDPTH is an actual measurement to the streambed.

Because MSBE and MINSBE values are determined using the water surface elevation at the gage, it is assumed that all discharge measurements have occurred along a

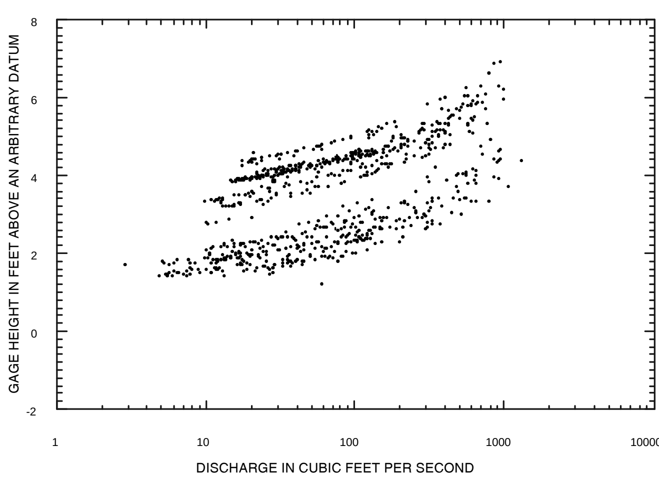



Figure 8. Corrected Rating Relation using rectified gage heights. There are still numerous lineations, but they occur over a significantly small range of 4 ft. Because this plot is generated from data that has been rectified to the contemporary gage datum, the variability is solely a consequence of changes in streambed elevation.

cross section adjacent to the gage. Actually, discharge measurements are often made at some distance from the gage. For example, DMs of Ashley Creek have been made up and downstream as much as 3000 ft from the gage. Assuming that all DMs were made at the gage implies that: 1) calculated mean depths per discharge are constant throughout the reach, 2) maximum depths measured at different locations can be analyzed together, and 3) the adjustability of the streambed is uniform throughout the reach. The assumption is unavoidable because the gage is the single point of elevation control that links the historic record to present day conditions.

The assumption that all DMs were made at the gage is central to MSBE and MINSBE analyses and must be substantiated. The location, measured discharge, and mean depth of a number of DMs for Ashley Creek are in table 2. From this table, it can be seen that mean depth, up and downstream, is essentially the same per discharge within a variability of 0.4 ft. Thus, at Ashley Creek, calculated mean depths are constant up and downstream, within a range of variability that is the same as the median particle size.

The variability associated with maximum depth measurements is a function of both streambed irregularities and different measurement locations. This variability is quantified by examining the standard deviation of the mean thalweg elevation for consecutive discharge measurements taken during periods of low flow. The record number, date, location, and thalweg elevations for consecutive discharge measurements are in table 3. The means and standard deviations of the thalweg elevations are also in table 3. The discharge measurements used in this analysis were selected because they represent relatively stable channel conditions during periods of base flow. By analyzing the bed elevations under low flow conditions, it is assumed that the channel does not change (no scour or fill of the channel) between measurements. Consequently, the differences between such consecutive bed elevation measurements are interpreted to represent the inherent measurement variability caused by streambed irregularities and different measurement locations.

For example, on September 26, 1951, a hydrographer measured discharge at the gage and the thalweg elevation was 6232.4 (table 3). One month later, discharge was again measured at the gage and the thalweg elevation was unchanged. Table 3 shows that the standard deviations of the mean thalweg elevations range from 0.0 to 0.4 ft and the average standard deviation is 0.1 ft. Thus, the inherent variability in the depth measurements caused by bed irregularities and the use of different measuring locations is small. Therefore, maximum depths measured at different locations within the reach can be analyzed together and the average variability between such measurements is ± 0.1 ft. The assumption that streambed adjustability is similar along the reach is verified by the MSBE analysis.

In an MSBE analysis, all MSBE data points are plotted in a time series (figure 10). The existence of a temporal trend in figure 10, which is derived from data measured up and downstream, indicates that the streambed adjustability is approximately uniform throughout the reach. A similar plot, using only data measured within 50 ft of the gage, shows the data to be consistent with the assumption (figure 11). Since this plot reveals the same temporal pattern of aggradation, stability, and degradation, the assumption of similar channel adjustability above and below the gage is justified.

While the smoothed trend of the MSBE provides temporal trends and spatial magnitudes, it is not the complete story. Since DMs are recorded almost monthly, it is possible to look at the data set in more detail and examine changes in the streambed at a monthly scale. However, this cannot be done using the MSBE data because they are calculated with top width measurements that are very different at high and low water stages. Figure 12 shows the relationship between the low and high water MSBEs along with the actual streambed elevation. Consequently,

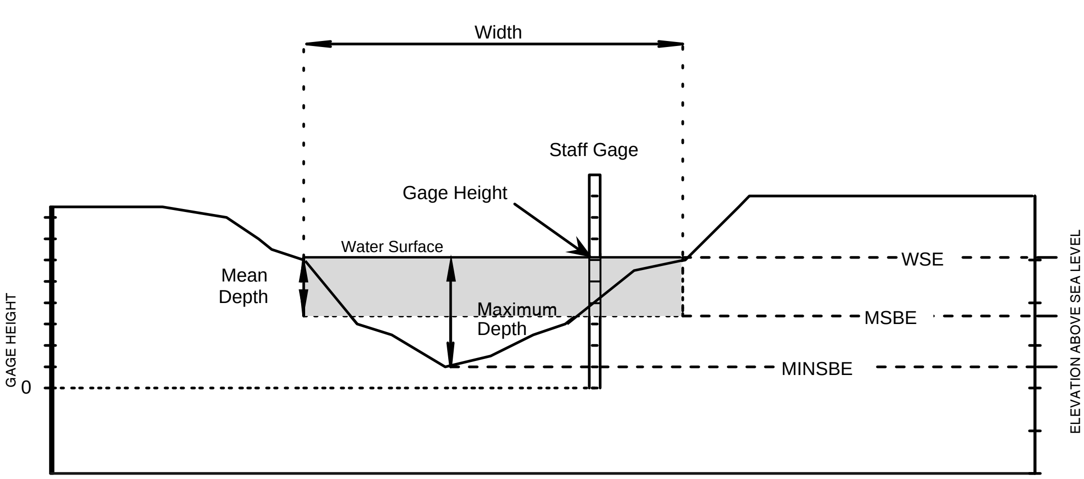



Figure 9. A channel cross-section showing the elements of equation (6) MSBE = WSE - MNDPTH and equation (7) MINSBE = WSE - MXDPTH. The mean depth is calculated from the continuity equation and the mean streambed elevation (MSBE) is calculated by subtracting the mean depth from the water surface elevation. In contrast, the minimum streambed elevation (MINSBE) is calculated using a measured depth to the streambed.

Table 2. Analysis of the variability associated when assuming the calculated mean depth, for a given discharge, to be equal at different locations above and below the gage.

| Record number | Date | Gage height (ft) | Discharge ($ft^3$/sec) | Mean depth (ft) | Location from gage (ft) | Difference in mean depth (ft) |
|---|---|---|---|---|---|---|
| 20 | 02/15/22 | 3.44 | 34.7 | 1.1 | 1000 | |
| 21 | 04/21/18 | 3.46 | 35.9 | 0.7 | 100 | 0.4 |
| 48 | 04/25/25 | 6.03 | 60.4 | 0.9 | 30.5 | |
| 56 | 08/30/26 | 6.06 | 69.6 | 0.9 | 20 | 0.0 |
| 106 | 08/7/38 | 6.18 | 97.3 | 1.3 | 500 | |
| 109 | 11/10/38 | 6.16 | 88.1 | 1.0 | 10 | 0.3 |
| 119 | 09/16/39 | 6.28 | 108 | 1.5 | 400 | |
| 120 | 10/14/39 | 6.26 | 94.8 | 1.4 | 500 | 0.1 |
| 134 | 01/10/41 | 5.89 | 32.5 | 1.0 | 100 | |
| 135 | 02/19/41 | 5.84 | 30 | 1.2 | 300 | |
| 136 | 04/18/41 | 5.84 | 24.6 | 1.1 | 250 | 0.1 |
| 142 | 08/17/41 | 6.09 | 96.2 | 1.0 | 500 | |
| 145 | 11/16/41 | 6.09 | 86.6 | 1.0 | 15 | 0.0 |
| 155 | 10/2/42 | 1.34 | 58.3 | 1.5 | 600 | |
| 156 | 10/16/42 | 1.33 | 52.4 | 1.1 | 600 | 0.4 |
| 177 | 09/27/44 | 1.42 | 55.2 | 1.1 | 500 | |
| 178 | 10/13/44 | 1.44 | 56.2 | 1.1 | 600 | 0.0 |
| 182 | 01/26/45 | 1.09 | 20.9 | 0.9 | 350 | |
| 183 | 03/12/45 | 1.07 | 19.6 | 0.9 | 400 | 0.0 |
| 238 | 12/2/48 | 0.64 | 21.5 | 0.7 | 25 | |
| 239 | 12/13/48 | 0.62 | 18.3 | 0.7 | -300 | 0.0 |
| 240 | 01/12/49 | 0.6 | 16.5 | 0.7 | -300 | |
| 243 | 03/1/49 | 0.55 | 16.3 | 0.6 | 25 | 0.1 |
| 255 | 11/4/49 | 0.88 | 41.2 | 1.0 | -500 | |
| 256 | 11/25/49 | 0.88 | 41.2 | 0.7 | 50 | 0.3 |
| 272 | 10/2/50 | 0.89 | 58.7 | 0.9 | -100 | |
| 273 | 10/25/50 | 0.86 | 53.4 | 1.2 | -250 | 0.3 |
| 340 | 03/21/55 | 0.58 | 17.7 | 0.6 | 40 | |
| 339 | 03/21/55 | 0.58 | 18.6 | 0.9 | -1000 | 0.3 |
| 400 | 12/17/57 | 0.2 | 28.9 | 0.5 | 20 | |
| 401 | 01/22/58 | 0.18 | 28.9 | 0.8 | -200 | 0.3 |
| 430 | 08/13/59 | 0.37 | 64.2 | 1.2 | -200 | |
| 439 | 04/11/60 | 0.39 | 65.6 | 0.8 | 20 | 0.4 |
| 435 | 01/18/60 | -0.11 | 14.7 | 0.5 | 150 | |
| 436 | 02/16/60 | -0.13 | 12.8 | 0.8 | -1000 | 0.3 |
| 497 | 11/20/63 | 0.85 | 18 | 1.0 | 300 | |
| 498 | 12/18/63 | 0.82 | 16.5 | 1.0 | -500 | 0.0 |
| 531 | 01/17/66 | 0.68 | 16.4 | 0.5 | 100 | |
| 533 | 03/30/66 | 0.67 | 14.7 | 0.4 | -300 | 0.0 |
| 546 | 02/6/67 | 0.47 | 11.8 | 0.7 | -600 | |
| 547 | 03/6/67 | 0.42 | 12 | 0.7 | -1000 | |
| 548 | 4/14/67 | 0.49 | 16.6 | 0.8 | -300 | 0.1 |
| 560 | 01/24/68 | 0.54 | 14.4 | 0.9 | -600 | |
| 562 | 04/1/68 | 0.54 | 13.8 | 0.9 | 0 | 0.0 |
| 573 | 01/15/69 | 0.95 | 13.2 | 0.7 | -500 | |
| 574 | 01/24/69 | 0.96 | 15.4 | 0.7 | 0 | 0.1 |
| 575 | 02/10/69 | 0.93 | 13.1 | 1.0 | -500 | |
| 576 | 03/17/69 | 0.9 | 10.9 | 0.9 | -300 | 0.1 |
| 584 | 10/13/69 | 1.15 | 32.3 | 1.0 | -600 | |
| 585 | 11/5/69 | 1.14 | 29.3 | 1.0 | -500 | 0.0 |
| 663 | 03/17/76 | 0.17 | 7.02 | 0.5 | -1000 | |
| 664 | 04/1/76 | 0.14 | 5.92 | 0.5 | -500 | 0.0 |
| 672 | 11/22/76 | 0.34 | 11.4 | 0.8 | -600 | |
| 673 | 12/9/76 | 0.33 | 11.7 | 0.6 | -500 | 0.2 |
| 686 | 12/5/77 | 0.7 | 10.6 | 1.1 | -500 | |
| 689 | 4/13/78 | 0.69 | 10.5 | 0.7 | -1000 | 0.4 |
| 698 | 10/23/78 | 0.6 | 13.6 | 1.1 | -500 | |
| 702 | 04/18/79 | 0.66 | 19.3 | 0.7 | 0 | 0.4 |
| 727 | 12/31/80 | 0.61 | 13.1 | 0.8 | -500 | |
| 730 | 04/13/81 | 0.62 | 19.5 | 0.8 | 20 | 0.0 |

Table 3. Analysis of variability in consecutive measurements of the Ashley Creek streambed elevation.

| Record number | Date | Measurement location (ft frm gage) | Thalweg elevation (ft) | Mean thalweg elevation (ft) | Standard deviation (ft) |
|---|---|---|---|---|---|
| 56 | 08/30/26 | 20 | 6232.9 | | |
| 57 | 10/23/26 | 10 | 6233.0 | 6232.9 | 0.1 |
| 62 | 08/12/27 | 0 | 6232.6 | | |
| 63 | 10/14/27 | 0 | 6232.8 | 6232.7 | 0.1 |
| 80 | 08/27/32 | 0 | 6232.7 | | |
| 81 | 10/6/32 | 50 | 6232.8 | 6232.8 | 0.1 |
| 83 | 08/9/33 | -500 | 6232.3 | | |
| 84 | 10/2/33 | -100 | 6232.6 | 6232.4 | 0.2 |
| 94 | 08/28/37 | 500 | 6231.5 | | |
| 96 | 10/28/37 | 500 | 6231.5 | 6231.5 | 0.0 |
| 107 | 09/12/38 | 30 | 6232.7 | | |
| 108 | 10/13/38 | 15 | 6232.6 | 6232.6 | 0.1 |
| 118 | 08/16/39 | 500 | 6232.0 | | |
| 119 | 09/16/39 | 400 | 6231.8 | 6231.9 | 0.1 |
| 119 | 09/16/39 | 400 | 6231.8 | | |
| 120 | 10/14/39 | 500 | 6231.9 | 6231.9 | 0.1 |
| 130 | 08/22/40 | 500 | 6232.1 | | |
| 131 | 09/21/40 | 500 | 6231.9 | 6232.0 | 0.1 |
| 131 | 09/21/40 | 500 | 6231.9 | | |
| 132 | 10/24/40 | 500 | 6232.0 | 6231.9 | 0.1 |
| 143 | 09/19/41 | 40 | 6232.4 | | |
| 144 | 10/20/41 | 40 | 6232.6 | 6232.5 | 0.1 |
| 154 | 08/13/42 | 800 | 6232.5 | | |
| 155 | 10/2/42 | 600 | 6232.1 | 6232.3 | 0.3 |
| 155 | 10/2/42 | 600 | 6232.1 | | |
| 156 | 10/16/42 | 600 | 6232.6 | 6232.4 | 0.4 |
| 165 | 09/7/43 | 500 | 6232.3 | | |
| 166 | 10/8/43 | 500 | 6232.7 | 6232.5 | 0.3 |
| 176 | 08/15/44 | 500 | 6232.4 | | |
| 177 | 09/27/44 | 500 | 6232.4 | 6232.4 | 0.0 |
| 177 | 09/27/44 | 500 | 6232.4 | | |
| 178 | 10/13/44 | 600 | 6232.5 | 6232.4 | 0.1 |
| 178 | 10/13/44 | 600 | 6232.5 | | |
| 179 | 10/15/44 | 600 | 6232.5 | 6232.5 | 0.0 |
| 190 | 08/23/45 | 500 | 6232.5 | | |
| 191 | 09/26/45 | 500 | 6232.4 | 6232.4 | 0.1 |
| 200 | 09/12/46 | 500 | 6232.6 | | |
| 201 | 09/13/46 | 500 | 6232.5 | 6232.6 | 0.1 |
| 201 | 09/13/46 | 500 | 6232.5 | | |
| 202 | 10/8/46 | 500 | 6232.4 | 6232.4 | 0.1 |
| 217 | 08/26/47 | 50 | 6232.3 | | |
| 218 | 09/9/47 | 30.5 | 6232.3 | 6232.3 | 0.0 |
| 218 | 09/9/47 | 30.5 | 6232.3 | | |
| 219 | 09/29/47 | 20 | 6232.3 | 6232.3 | 0.0 |
| 219 | 09/29/47 | 20 | 6232.3 | | |
| 220 | 10/7/47 | 75 | 6232.2 | 6232.3 | 0.1 |
| 234 | 08/10/48 | 50 | 6232.4 | | |
| 235 | 09/24/48 | -100 | 6232.6 | 6232.5 | 0.1 |
| 235 | 09/24/48 | -100 | 6232.6 | | |
| 236 | 10/29/48 | -100 | 6232.6 | 6232.6 | 0.0 |
| 253 | 08/11/49 | -350 | 6232.1 | | |
| 254 | 09/7/49 | -300 | 6232.1 | 6232.1 | 0.0 |
| 270 | 08/24/50 | 25 | 6232.4 | | |
| 271 | 09/9/50 | 50 | 6232.5 | 6232.4 | 0.1 |
| 271 | 09/9/50 | 50 | 6232.5 | | |
| 272 | 10/2/50 | -100 | 6232.2 | 6232.4 | 0.2 |
| 284 | 08/1/51 | 0 | 6232.5 | | |
| 285 | 09/12/51 | -50 | 6232.5 | 6232.5 | 0.0 |
| 285 | 09/12/51 | -50 | 6232.5 | | |
| 286 | 09/26/51 | 0 | 6232.4 | 6232.4 | 0.1 |
| 286 | 09/26/51 | 0 | 6232.4 | | |
| 287 | 10/25/51 | 0 | 6232.4 | 6232.4 | 0.0 |
| 299 | 08/19/52 | 50 | 6232.5 | | |
| 300 | 09/18/52 | 40 | 6232.4 | 6232.4 | 0.1 |
| 300 | 09/18/52 | 40 | 6232.4 | | |
| 301 | 10/17/52 | 30 | 6232.1 | 6232.3 | 0.2 |
| 316 | 08/26/53 | 20 | 6232.5 | | |
| 317 | 09/29/53 | 30 | 6232.4 | 6232.4 | 0.1 |
| 331 | 08/19/54 | 40 | 6232.4 | | |
| 332 | 09/22/54 | 40 | 6232.4 | 6232.4 | 0.0 |
| 332 | 09/22/54 | 40 | 6232.4 | | |
| 333 | 10/26/54 | 0 | 6232.2 | 6232.3 | 0.1 |
| 352 | 08/12/55 | 40 | 6232.4 | | |
| 353 | 09/2/55 | 40 | 6232.5 | 6232.4 | 0.1 |
| 353 | 09/2/55 | 40 | 6232.5 | | |
| 354 | 09/19/55 | 0 | 6232.2 | 6232.4 | 0.2 |
| 354 | 09/19/55 | 0 | 6232.2 | | |
| 355 | 10/19/55 | 20 | 6232.1 | 6232.1 | 0.1 |
| 372 | 08/10/56 | 0 | 6232.5 | | |
| 373 | 09/12/56 | 0 | 6232.3 | 6232.4 | 0.1 |
| 373 | 09/12/56 | 0 | 6232.3 | | |
| 374 | 10/18/56 | 0 | 6232.5 | 6232.4 | 0.1 |
| 374 | 10/18/56 | 0 | 6232.5 | | |
| 375 | 10/18/56 | 0 | 6232.3 | 6232.4 | 0.1 |
| 395 | 08/2/57 | 0 | 6231.9 | | |
| 396 | 08/22/57 | 0 | 6232.2 | 6232.1 | 0.2 |
| 396 | 08/22/57 | 0 | 6232.2 | | |
| 397 | 09/24/57 | 0 | 6232.1 | 6232.1 | 0.1 |
| 397 | 09/24/57 | 0 | 6232.1 | | |
| 398 | 10/24/57 | 40 | 6232.1 | 6232.1 | 0.0 |
| 412 | 08/5/58 | 75 | 6232.3 | | |
| 413 | 09/3/58 | 0 | 6232.3 | 6232.3 | 0.0 |
| 413 | 09/3/58 | 0 | 6232.3 | | |
| 414 | 10/1/58 | 0 | 6232.2 | 6232.3 | 0.1 |
| 431 | 09/22/59 | 50 | 6232.2 | | |
| 432 | 10/13/59 | 0 | 6232.1 | 6232.1 | 0.1 |
| 447 | 08/11/60 | 0 | 6232.1 | | |
| 448 | 09/14/60 | 0 | 6232.2 | 6232.1 | 0.1 |
| 448 | 09/14/60 | 0 | 6232.2 | | |
| 449 | 10/4/60 | 10 | 6232.3 | 6232.3 | 0.1 |
| 449 | 10/4/60 | 10 | 6232.3 | | |
| 450 | 10/21/60 | 10 | 6232.2 | 6232.3 | 0.1 |
| 466 | 8/17/61 | 0 | 6232.3 | | |
| 467 | 9/11/61 | 0 | 6232.4 | 6232.4 | 0.1 |

Table 3.(Continued)

| Record number | Date | Measurement location (ft frm gage) | Thalweg elevation (ft) | Mean thalweg elevation (ft) | Standard deviation (ft) |
|---|---|---|---|---|---|
| 467 | 09/11/61 | 0 | 6232.4 | | |
| 468 | 10/16/61 | 0 | 6232.4 | 6232.4 | 0.0 |
| 479 | 08/15/62 | 0 | 6232.3 | | |
| 480 | 09/10/62 | 0 | 6232.5 | 6232.4 | 0.1 |
| 480 | 09/10/62 | 0 | 6232.5 | | |
| 481 | 10/11/62 | 10 | 6232.2 | 6232.4 | 0.2 |
| 495 | 09/19/63 | 50 | 6232.1 | | |
| 496 | 10/16/63 | 100 | 6232.3 | 6232.2 | 0.1 |
| 510 | 08/10/64 | 50 | 6231.1 | | |
| 511 | 09/17/64 | 75 | 6231.2 | 6231.1 | 0.1 |
| 511 | 09/17/64 | 5 | 6231.2 | | |
| 512 | 10/14/64 | 100 | 6231.1 | 6231.1 | 0.1 |
| 526 | 08/9/65 | 50 | 6231.0 | | |
| 527 | 09/19/65 | 50 | 6231.1 | 6231.1 | 0.1 |
| 527 | 09/19/65 | 50 | 6231.1 | | |
| 528 | 10/12/65 | 50 | 6231.1 | 6231.1 | 0.0 |
| 541 | 08/18/66 | -200 | 6230.4 | | |
| 542 | 09/8/66 | -200 | 6230.3 | 6230.4 | 0.1 |
| 554 | 08/9/67 | -150 | 6229.9 | | |
| 555 | 09/6/67 | -200 | 6229.8 | 6229.9 | 0.1 |
| 555 | 09/6/67 | -200 | 6229.8 | | |
| 556 | 10/9/67 | -200 | 6230.3 | 6230.1 | 0.4 |
| 569 | 09/20/68 | 0 | 6229.4 | | |
| 570 | 10/28/68 | -500 | 6229.7 | 6229.6 | 0.2 |
| 582 | 08/12/69 | -500 | 6229.1 | | |
| 583 | 09/10/69 | -20 | 6229.3 | 6229.2 | 0.1 |
| 583 | 09/10/69 | -20 | 6229.3 | | |
| 584 | 10/13/69 | -600 | 6229.5 | 6229.4 | 0.1 |
| 595 | 08/6/70 | -300 | 6228.9 | | |
| 596 | 09/8/70 | -300 | 6229.5 | 6229.2 | 0.4 |
| 596 | 09/8/70 | -300 | 6229.5 | | |
| 597 | 10/7/70 | -500 | 6229.1 | 6229.3 | 0.3 |
| 607 | 08/6/71 | 10 | 6229.2 | | |
| 608 | 09/13/71 | 0 | 6229.4 | 6229.3 | 0.1 |
| 608 | 09/13/71 | 0 | 6229.4 | | |
| 609 | 10/5/71 | -10 | 6229.4 | 6229.4 | 0.0 |
| 619 | 08/15/72 | -10 | 6229.6 | | |
| 620 | 09/12/72 | -10 | 6229.7 | 6229.6 | 0.1 |
| 620 | 09/12/72 | -10 | 6229.7 | | |
| 621 | 10/10/72 | -10 | 6229.6 | 6229.6 | 0.1 |
| 632 | 08/8/73 | -10 | 6229.0 | | |
| 633 | 09/14/73 | 0 | 6229.2 | 6229.1 | 0.1 |
| 633 | 09/14/73 | 0 | 6229.2 | | |
| 634 | 10/8/73 | 0 | 6229.4 | 6229.3 | 0.1 |
| 643 | 08/8/74 | 0 | 6229.1 | | |
| 644 | 09/5/74 | 0 | 6228.9 | 6229.0 | 0.1 |
| 644 | 09/5/74 | 0 | 6228.9 | | |
| 645 | 10/8/74 | 10 | 6229.3 | 6229.1 | 0.3 |
| 656 | 08/12/75 | 0 | 6228.8 | | |
| 657 | 09/22/75 | 0 | 6228.6 | 6228.7 | 0.1 |
| 657 | 09/22/75 | 0 | 6228.6 | | |
| 658 | 10/8/75 | 0 | 6228.7 | 6228.6 | 0.1 |
| 669 | 08/13/76 | -1000 | 6229.5 | | |
| 670 | 09/10/76 | -1000 | 6229.2 | 6229.4 | 0.2 |
| 697 | 09/22/78 | -500 | 6228.5 | | |
| 698 | 10/23/78 | -500 | 6228.5 | 6228.5 | 0.0 |
| 710 | 09/10/79 | 0 | 6229.1 | | |
| 711 | 10/24/79 | 0 | 6229.0 | 6229.1 | 0.1 |
| 723 | 08/13/80 | 0 | 6228.9 | | |
| 724 | 09/22/80 | 10 | 6229.0 | 6228.9 | 0.1 |
| 724 | 09/22/80 | 10 | 6229.0 | | |
| 725 | 10/8/80 | 10 | 6229.2 | 6229.1 | 0.1 |
| 746 | 08/26/82 | 5 | 6229.3 | | |
| 747 | 09/30/82 | 0 | 6229.2 | 6229.3 | 0.1 |
| 747 | 09/30/82 | 0 | 6229.2 | | |
| 748 | 10/29/82 | -1000 | 6229.1 | 6229.1 | 0.1 |
| 759 | 08/29/83 | -325 | 6228.8 | | |
| 760 | 10/13/83 | -325 | 6228.7 | 6228.8 | 0.1 |
| 769 | 08/23/84 | 0 | 6229.0 | | |
| 770 | 10/12/84 | 0 | 6228.9 | 6228.9 | 0.1 |
| 778 | 08/6/85 | -100 | 6228.9 | | |
| 779 | 10/22/85 | 15 | 6228.3 | 6228.6 | 0.4 |
| 779 | 10/22/85 | 15 | 6228.3 | | |
| 780 | 10/24/85 | -750 | 6228.3 | 6228.3 | 0.0 |
| 790 | 08/26/86 | 10 | 6228.7 | | |
| 791 | 10/10/86 | 10 | 6228.6 | 6228.6 | 0.1 |
| 800 | 08/28/87 | -150 | 6228.7 | | |
| 801 | 10/9/87 | -150 | 6229.2 | 6228.9 | 0.4 |
| 809 | 08/31/88 | -150 | 6228.7 | | |
| 810 | 10/7/88 | -200 | 6228.7 | 6228.7 | 0.0 |
| 810 | 10/7/88 | -200 | 6228.7 | | |
| 811 | 10/27/88 | -10 | 6228.9 | 6228.8 | 0.1 |
| 818 | 08/10/89 | -30 | 6228.9 | | |
| 819 | 08/31/89 | -15 | 6228.9 | 6228.9 | 0.0 |
| 819 | 08/31/89 | -15 | 6228.9 | | |
| 820 | 10/4/89 | -10 | 6229.0 | 6228.9 | 0.1 |
| 820 | 10/4/89 | -10 | 6229.0 | | |
| 821 | 10/26/89 | -20 | 6228.9 | 6228.9 | 0.1 |
| 828 | 08/29/90 | 5 | 6228.8 | | |
| 829 | 09/27/90 | 5 | 6228.7 | 6228.8 | 0.1 |
| 829 | 09/27/90 | 5 | 6228.7 | | |
| 830 | 10/15/90 | 0 | 6228.9 | 6228.8 | 0.1 |
| 839 | 09/11/91 | 5 | 6229.0 | | |
| 840 | 10/3/91 | -50 | 6229.0 | 6229.0 | 0.0 |
| 849 | 08/3/92 | -5 | 6229.2 | | |
| 850 | 09/1/92 | 5 | 6229.1 | 6229.1 | 0.1 |
| 850 | 09/1/92 | 5 | 6229.1 | | |
| 851 | 10/7/92 | -80 | 6229.2 | 6229.1 | 0.1 |
| 858 | 08/19/93 | 0 | 6228.4 | | |
| 859 | 09/17/93 | -400 | 6228.7 | 6228.6 | 0.2 |
| 859 | 09/17/93 | -400 | 6228.7 | | |
| 860 | 10/7/93 | 100 | 6228.7 | 6228.7 | 0.0 |

*Range of standard deviatrions (ft): 0.0 to 0.4*

*Mean of standard deviations (ft): 0.1*

*Median of standard deviations (ft): 0.1*

*Mode of standard deviations (ft): 0.1*

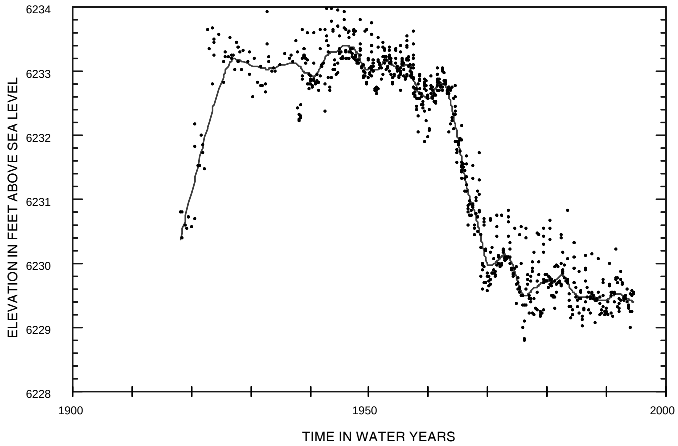



Figure 10. Plot of the mean streambed elevation (MSBE) using all data. This plot depicts a streambed at a station through time and shows that the streambed aggraded during the early 1920s, was stable for approximately 38 years, and then degraded rapidly during the early 1960s. The smooth curve through the data delineates the temporal trend and represents the application of a Stineman Function to the data. The output of this function has geometric weight applied to the current point and ±10% of the data range to arrive at the smoothed curve.

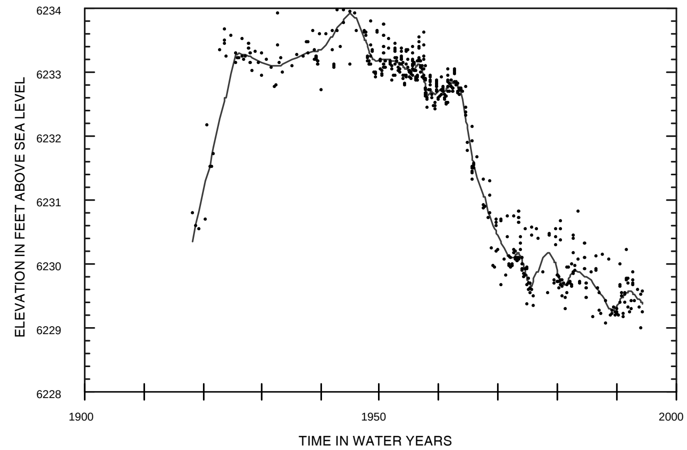



Figure 11. Plot of the mean streambed elevation (MSBE) using only measurements made within 50 ft of the gage. Since the plot shows the same trends as figure 12, the analytical assumption that streambed adjustability is similar above and below the gage is justified.

to examine actual streambed changes at a monthly scale, it is necessary to generate a time series of the thalweg or minimum streambed elevation. Plots of the minimum streambed elevation are developed in the same way that MSBE plots are generated.

Figure 13 is a comparison of MINSBE and MSBE data between 1962 to 1973. Both plots show net degradation over multiple decades and annual scour and fill of the streambed. However, the fills (bed elevation increases) of the MSBE plot are not real and actually reflect large changes in channel top width (figure 12). In contrast, the MINSBE plot is based on actual measurements to the streambed. Therefore, the bed elevation increases exhibited in the MINSBE plots represent true channel filling.

Because MSBE and MINSBE analyses provide strong evidence of channel adjustability and are dependent upon a common gage datum, it is imperative to have accounted for all datum changes throughout the period of record. Fortunately, failure to account for a datum change in the analysis is rather obvious. Figure 14 is an MSBE analysis of the Ashley Creek data without correcting for datum changes. In this plot, unrecognized datum changes occur as large, abrupt jumps in the data distribution. Consequently, if the plots show smooth trends and no abrupt changes, it is likely that all datum changes have been recognized. Close inspection of figure 10 reveals an abrupt jump in 1957 that suggests a datum change. In this case, a

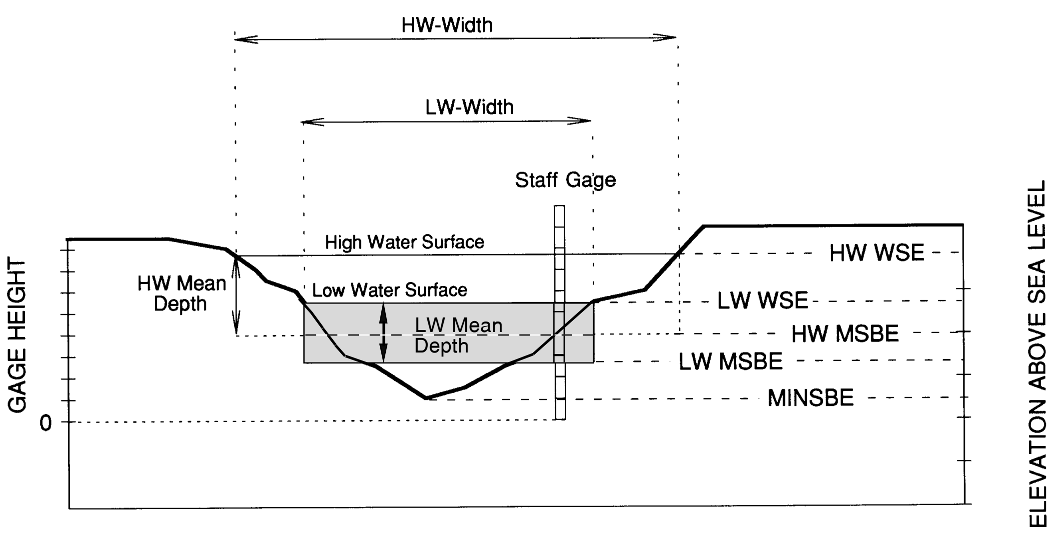



Figure 12. The relationship between mean streambed elevations (MSBE) for high and low flows along with the minimum streambed elevation (MINSBE). This plot shows how fluctuations in the water level alone can result in MSBE values that indicate scour and fill. In contrast, because MINSBE values are always calculated using measured depths to the streambed, they reflect true changes in the streambed. HW=high water, LW=low water, WSE=water surface.

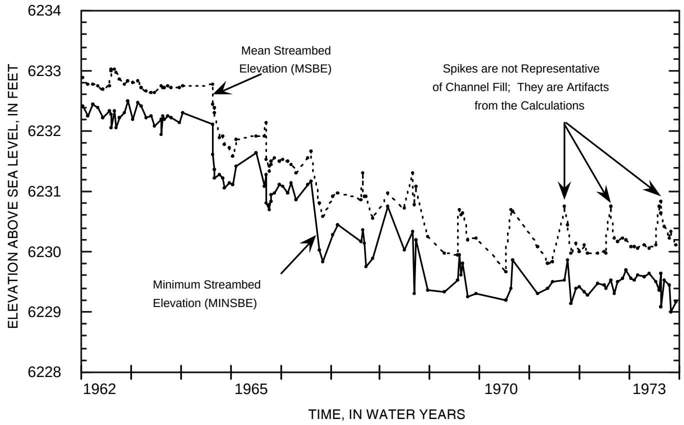



Figure 13. Comparison of mean streambed elevation (MSBE) and minimum streambed elevation (MINSBE) plots for Ashley Creek between 1962 and 1973, which was the most dramatic period of streambed degradation. The MSBE plot shows annual spikes that suggest channel filling. These spikes do not represent real channel filling because the MSBE data is based on calculations using channel top width. The MINSBE plot is based on actual measurements to the streambed and, therefore, the spikes exhibited in the MINSBE plot represent true episodes of scour or fill.

flood occurred, and the hydrographer noted that the channel had scoured; a scour event in 1957 is precisely what the MSBE plot indicates. MSBE and MINSBE analyses quantify the magnitude of streambed adjustability, are sensitive enough to distinguish the effect of individual flood events, and delineate discrete time periods of channel change. In the Ashley Creek example, these time periods

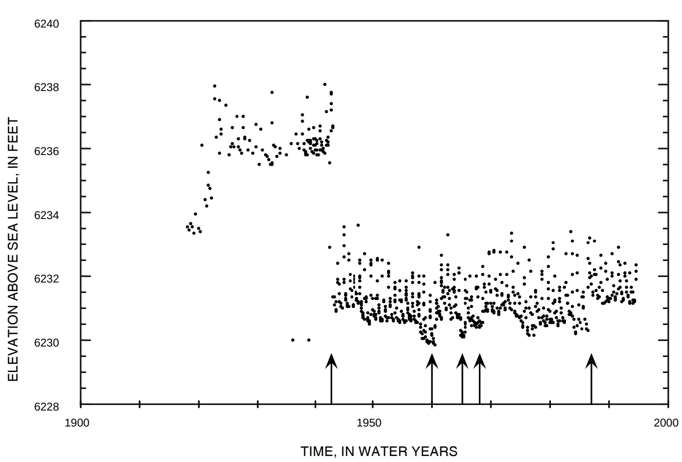



Figure 14. Plot of the mean streambed elevation without rectifying the gage heights. This plot contains 5 jumps (arrows) in the data distribution that are indicative of the datum changes (see figure 7).

are: 1917 to 1924, 1925 to 1961, 1962 to 1967, and 1976 to 1994. Similarly, the MINSBE plots show streambed adjustments on a month-to-month scale.

## Hydraulic Geometry

The hydraulic geometry of a stream is a statistical characterization that quantifies the channel dimensions (Leopold and Maddock 1953). Hydraulic geometry analyses define the guiding relations of channel dimensions to discharge, reveals which variables are most adjustable, and further quantifies channel response to aggradation, degradation, and stability. If the formative discharges of the channel are altered, theory predicts a change in the hydraulic geometry (Singh 1992). Standard hydraulic geometry relations include regression analyses of velocity, width, and depth as a function of discharge. By comparing the hydraulic geometry relations for the discrete intervals of time as delineated by the MSBE analysis, it is possible to quantify specific rates of adjustability that coincide with periods of aggradation, degradation, and stability. Such relations may be used as templates to assess whether or not other reaches of the same stream are undergoing aggradation, degradation, or relative stability.

Figure 15 shows hydraulic geometry plots for Ashley Creek created from all data for the period of record. If the data are sorted according to the time periods delineated by the MSBE plots, the resultant hydrogeometric relations can be compared and contrasted to quantify channel response during the periods of aggradation, degradation, and stability. Table 4 shows time-specific regression relations, and figure 16 shows the plots of these relations. In general, these plots show that the hydraulic geometry has changed only slightly since 1924 and that width and depth exhibit the most variability. The plots also indicate that periods of:

- rapid degradation (1962-1967) are characterized by increases in the rate at which depth changes with discharge;
- rapid aggradation are characterized by increases in the rate at which width changes with discharge; and
- stability are characterized by increases in the rate at which velocity changes with discharge.

These regression comparisons are based on a visual analysis and are therefore informal. More formal comparisons can be made by examining the regressions within a rigorous statistical context as described by Neter et al. (1989).

In addition to hydraulic geometry analyses, changes in channel width and depth can be further examined through time series analyses. Time series of depth (streambed elevation) were discussed in the MSBE and MINSBE analyses; temporal changes in width are discussed below.

## Change in Width

The purpose of width analysis is to assess changes in the bank-to-bank channel morphology. A straightforward change-in-width-through-time analysis, using all DMs from up and downstream, is unjustified because the variability of stream width, up and downstream, for a specific discharge can be significant. For example, stream widths for a specific discharge along Ashley Creek can vary as much as 30%. This variability is a reflection of the channel complexity that is accentuated during low discharges and

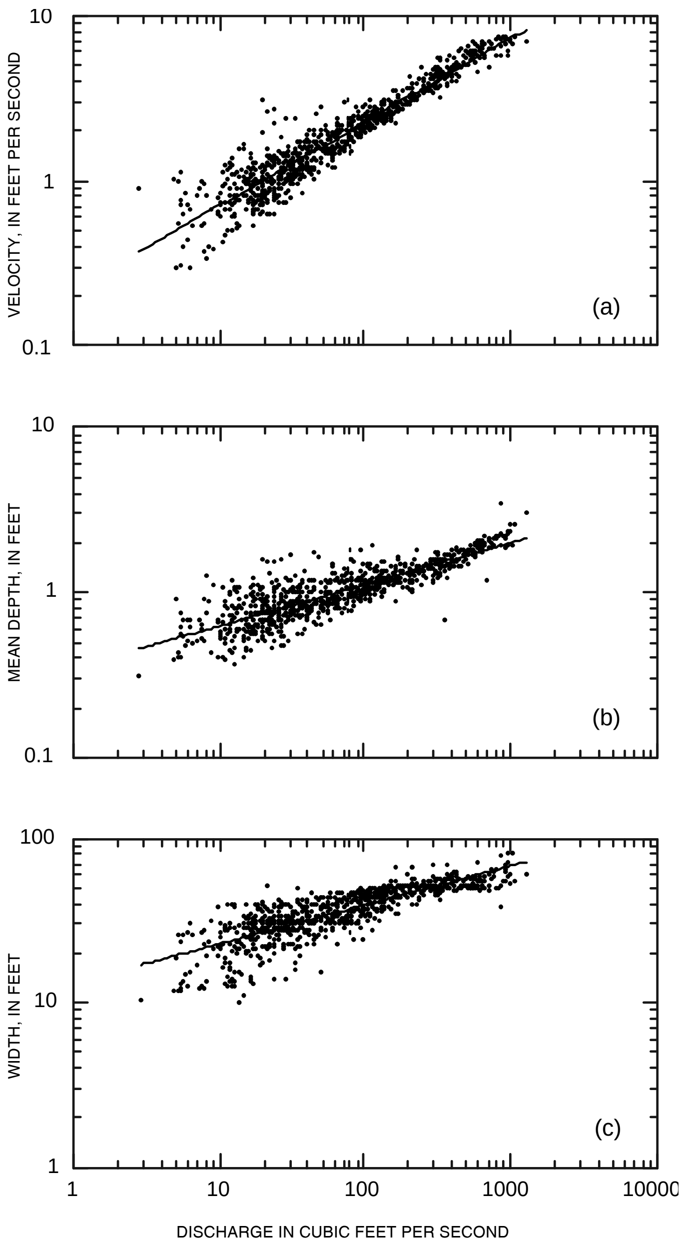



Figure 15. Hydraulic geometry plots of Ashley Creek. These plots use all data for the entire period of record: (a) velocity vs. discharge, (b) mean depth vs. discharge, and (c) width vs. discharge.

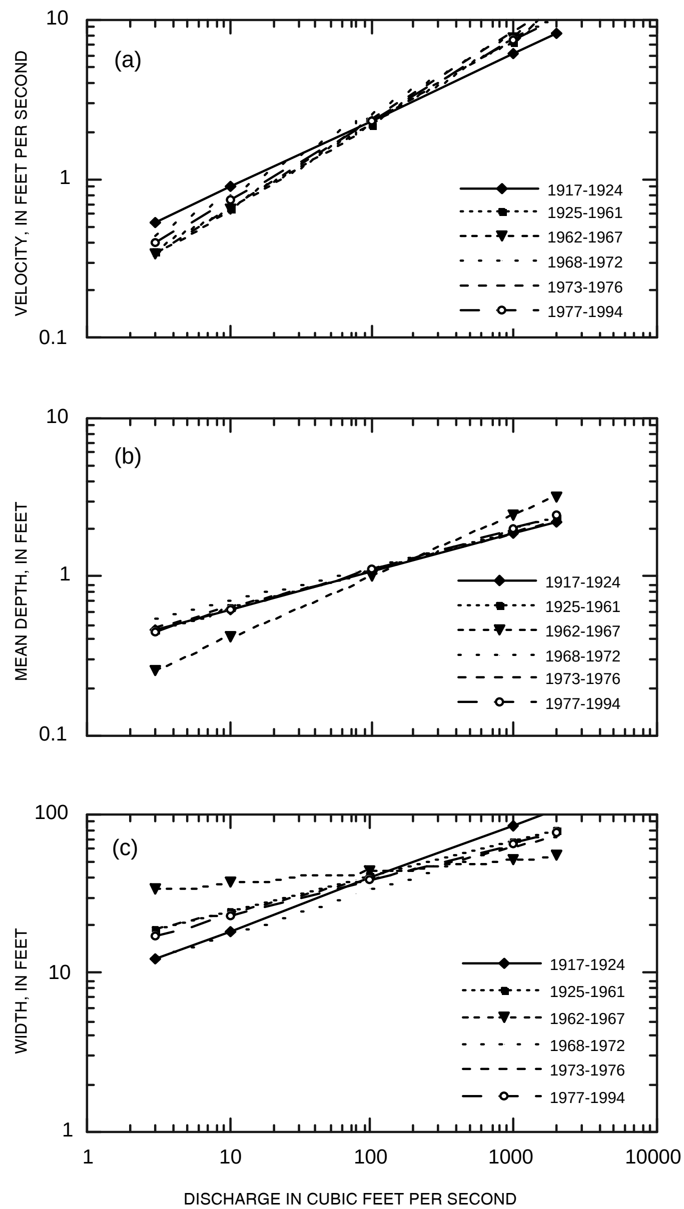



Figure 16. Temporal trends of the hydraulic geometry. These plots are comparisons of the hydraulic geometry regression relations for unique time periods of aggradation, stability, and degradation: (a) velocity vs. discharge, (b) mean depth vs. discharge, and (c) width vs. discharge. The points shown are calculated values; their only purpose is to help distinguish the trends of particular time periods.

Table 4. Hydraulic geometry regression relations for specific time periods.

| Time Periods | Velocity | Mean Depth | Width |
|---|---|---|---|
| 1917-1924 | $v = 0.33763*Q^{0.41938}$ | $d = 0.34764*Q^{0.24578}$ | $w = 8.5388*Q^{0.33311}$ |
| 1925-1961 | $v = 0.19547*Q^{0.52241}$ | $d = 0.35434*Q^{0.25115}$ | $w = 14.916*Q^{0.21922}$ |
| 1962-1967 | $v = 0.18656*Q^{0.541}$ | $d = 0.16926*Q^{0.38694}$ | $w = 31.608*Q^{0.073119}$ |
| 1968-1972 | $v = 0.254*Q^{0.49929}$ | $d = 0.42655*Q^{0.21701}$ | $w = 9.2339*Q^{0.28355}$ |
| 1973-1976 | $v = 0.18691*Q^{0.55255}$ | $d = 0.36968*Q^{0.23762}$ | $w = 14.878*Q^{0.20575}$ |
| 1977-1994 | $v = 0.2288*Q^{0.50287}$ | $d = 0.34115*Q^{0.25729}$ | $w = 13.359*Q^{0.23101}$ |

*v = velocity, d = mean depth, w = width, Q = discharge*

overbank flood flows. Therefore, changes in width-through-time (WTT) analyses must exclude both low-flow and overbank discharges.

The exclusion of low discharges is necessary because at such flow, water edges are affected by the distribution of instream features (such as channel bars), rather than the channel banks. Similarly, the exclusion of flood-stage discharges is necessary because overbank flow widths can be highly variable. In both cases, the width measurements are not the bankfull dimensions. Consequently, changes in channel width are best demonstrated by DMs for a range of medium to high discharges that nearly fill the bankfull channel. In Ashley Creek, a range of discharges between 40 and 85% of the mean annual flood were suitable for width analysis. The need to restrict width analysis to a range of discharges is shown in figure 17, which indicates almost 20 ft of channel narrowing through time. Channel narrowing is consistent with the MSBE, MINSBE, and hydraulic geometry analyses, which show that the channel has incised.

## Cross Sections

As discussed, each DM includes a measured cross-section. One of the more illustrative quantifications of geomorphic change is to overlay cross-sections measured at the same location but at different times. Similarly, contemporary surveys of historic cross-sections can also be performed (figure 18). To perform these overlays, it is necessary to know where the sections were measured. For measurements made between permanent benchmarks that can be relocated, such as a cableway, the overlays and surveys are straightforward. More typically, DMs are performed wherever the most accurate measurement can be made, and precise locations are not recorded on the DM. Instead, the distance from the gage is usually estimated, and notes such as "1/4 mile above," "50 ft below

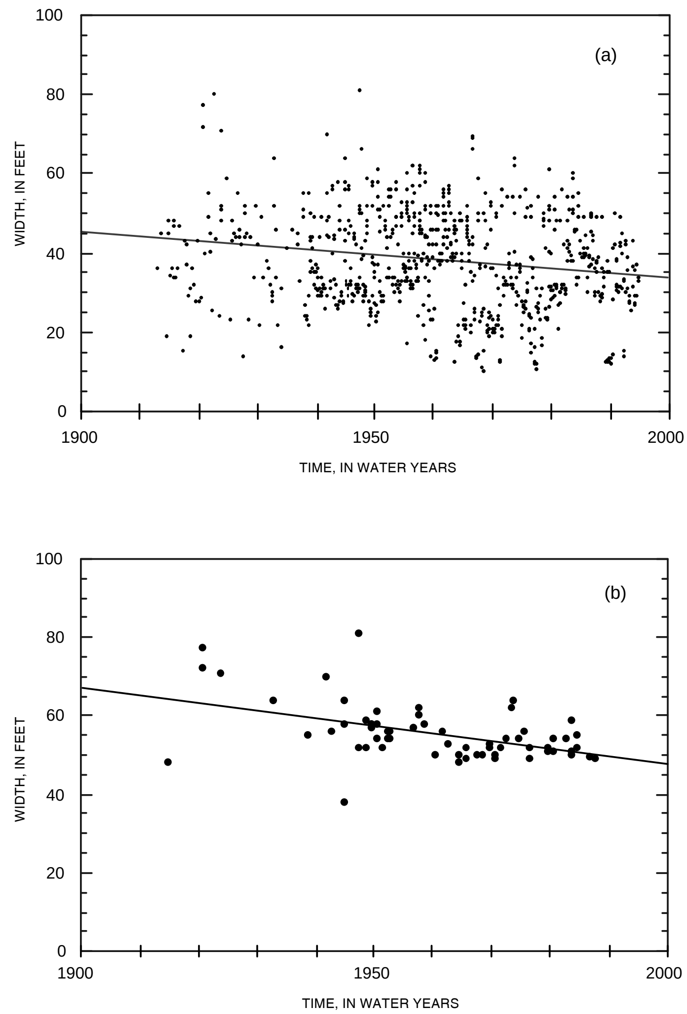



Figure 17. Stream width changes through time. The top plot incorporates all width measurements for the period of record; it shows slight narrowing and substantial scatter. The bottom plot only uses width measurements associated with a range of discharges between 500 and 1000 $ft^3$/sec and shows 15 to 20 ft of channel narrowing.

gage," and "at gage" are recorded. These cross-sections are measured from one water edge to the other and are not typically measured in relation to permanent benchmarks; therefore, overlays and surveys of historic cross-sections include elements of error with regard to location. The error associated with estimating the distance from the gage is assumed to increase the farther the hydrographer was from the gage. Consequently, only historic sections that were described as being within 20 ft of the gage or cableway were compared. Typically, only cross sections measured at the cableway were resurveyed. The error associated with the laterally unconstrained aspect of the historic sections appears to be uncorrectable.

Once a historic location has been selected for survey, the distances from initial point and depth measurements recorded on the particular DM are entered into the computer. This information is on the back pages of the DM (figure 3). These depth measurements are relative to a water-surface elevation that is defined by the gage-height recorded on the DM. Thus, no matter where the section was measured the only elevation reference is that of the gage height recorded during the measurement. For purposes of cross-section overlays, the water surface elevation of the resurveyed section must be that of the gage height at the time of resurvey. Once the original and resurveyed sections are entered in the computer spreadsheets, they are plotted together. As indicated, the original section may be laterally unconstrained and a suitable horizontal depiction must be visually determined (figure 18).

In general, the replicated cross-sections should mimic the changes determined in the MINSBE and WTT analyses. Moreover, the replications can provide insights into the historic relation between the channel and discharge. For example, a 1926 cross section measured at the cableway on Ashley Creek is compared with a 1995 resurvey (figure 18). Both sections are plotted with lines indicating discharges of 228 $ft^3$/sec and the mean annual flood. This figure shows that before incision, the mean annual flood (~bankfull) inundated the upper surface. Since the upper surface is no longer inundated, it is now an abandoned floodplain or terrace. Critical to this interpretation is that flow velocity of these discharges during the different time periods be essentially the same. Using the hydraulic geometry relations in table 4, the difference in flow velocity at bankfull for both time periods is less than 2%. Thus, the interpretation is supported and, like the other analyses, this replication of cross-section data indicates channel incision and narrowing.

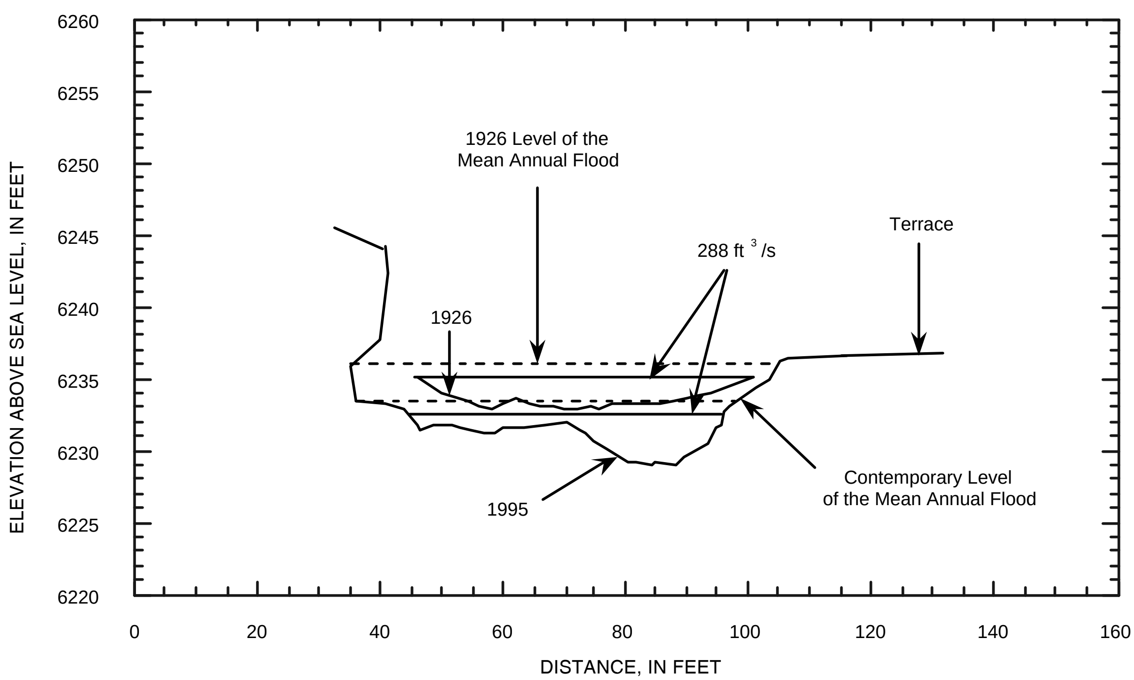



Figure 18. Comparison of cross-sections measured in 1926 and 1995 at the Ashley Creek cableway. Although elevation control is provided by the gage and reference marks, there are no lateral controls with which to fix the ends of the 1926 cross section. Consequently, the overlay is fitted by eye. This figure shows both sections at a discharge of 288 $ft^3$/sec, the 1926 level of the mean annual flood, and the contemporary level of the mean annual flood. This figure indicates that before the channel degradation of the early 1960s, mean annual flood flows represented incipient flooding of the valley flat.

## Determination of Discharges

Once geomorphic change has been documented and the timing of adjustment established, the geomorphic and hydrologic histories can be compared and contrasted. This is accomplished by comparing the MSBE, MINSBE, or WTT plots with different hydrographs for the period of record. Three of the more informative hydrographs to develop are the: 1) annual total runoff volumes, 2) annual instantaneous peak floods, and 3) daily mean discharges. These hydrologic data sets are in the USGS Water Supply Papers, CD-ROMs, and on the Internet. For example, the MINSBE plot of Ashley Creek is combined with the annual runoff volumes (figure 19) and peak flood data (figure 20). Similarly, the MINSBE plot is compared with both daily mean discharge data and peak flood data in figure 21. Figure 19 shows that no anomalous increases or decreases in the overall volume of water flowing through the channel have occurred over the period of record. Consequently, the geomorphic changes recorded in the MiNSBE plot are probably not the result of changes (i.e., regulation) in the annual volume of water flowing through the channel.

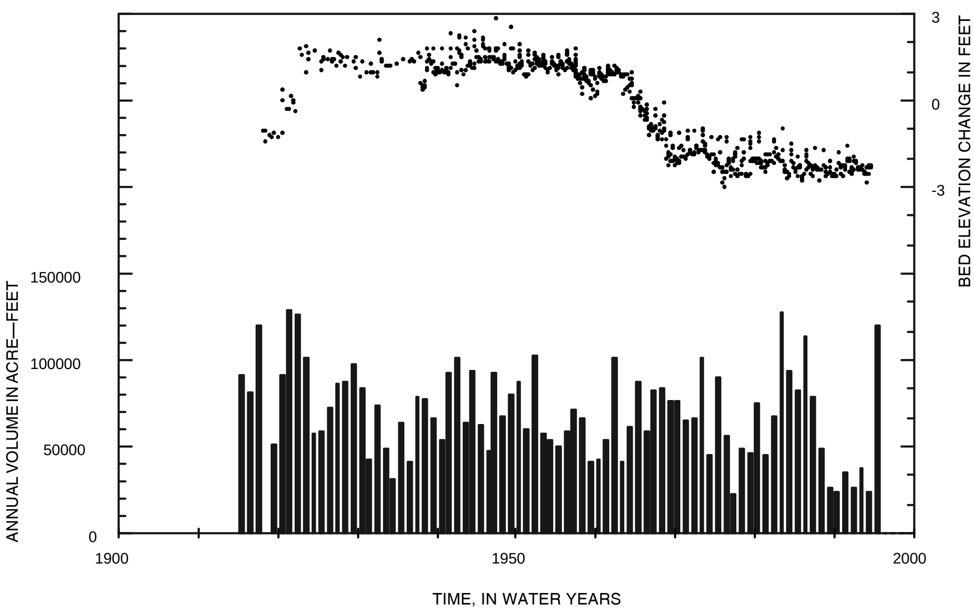



Figure 19. Comparison of minimum streambed elevations to annual runoff volumes. This plot shows no dramatic increases or decreases in volume of runoff and there is no correlation between bed elevation changes and years of high runoff.

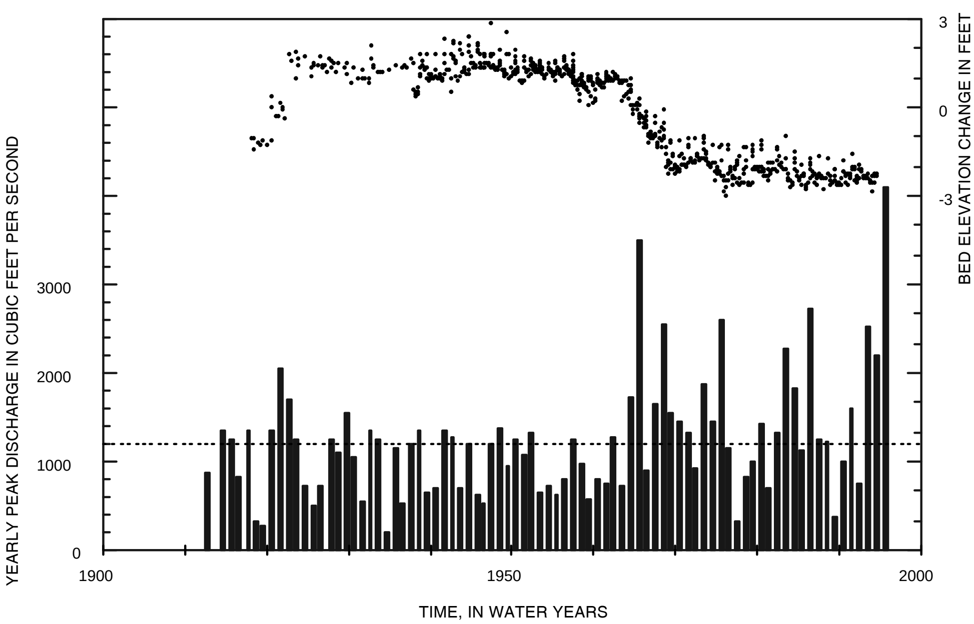



Figure 20. Comparison of minimum streambed elevations to annual peak discharges. This plot indicates that changes in the streambed may be related to changes in the hydrologic regime, but peak flood events are not directly responsible for streambed elevation changes. The dashed horizontal line delineates the mean annual flood of 1200 ft$^3$/sec.

Figure 20 is the comparison of the MINSBE plot to the annual instantaneous discharge peaks and some correlations are visible. Specifically, water years 1920 through 1923 were consecutive years of large peak flows that corresponded with streambed aggradation. Between 1925 and 1963, peak discharges were relatively low and uniform. Coincidentally, no dramatic changes occurred in the streambed. Between 1964 and 1968, the streambed degraded substantially, which is correlated with an abrupt increase in the magnitude of peak floods. High peak discharges occurred throughout the 1970s, 1980s, and 1990s, but large magnitudes of streambed change did not occur. Thus, the same hydrologic conditions do not necessarily generate the same channel response in Ashley Creek, and the role of large floods in affecting channel change is variable.

A closer look at the data reveals that the substantial channel degradation occurring in the mid 1960s was not directly related to high discharges. Figure 21 shows the changes in the Ashley Creek streambed between 1962 and 1973. As shown, the bed adjusts (fills and/or scours) as a function of the rise and fall of the annual hydrograph. In

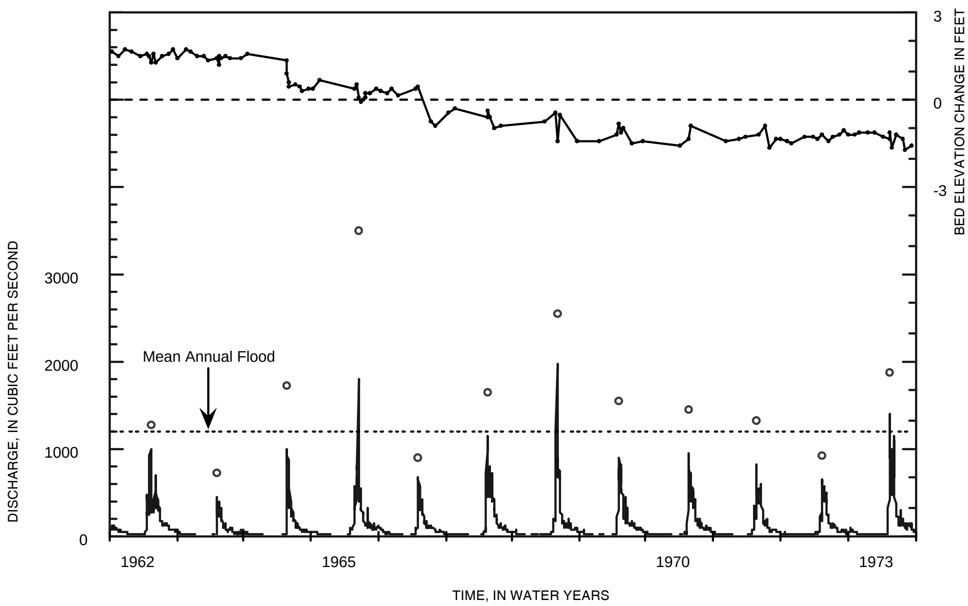



Figure 21. Comparison of minimum streambed elevations to annual hydrographs from 1962 to 1973. The hydrographs are generated using daily mean discharge values. The open circles are the instantaneous peak floods for each year. Annual fill and scour is indicated and a net degradation of approximately 3 ft is shown. Note that the degradation was accomplished progressively by frequently occurring flows and that large-magnitude floods do not cause large bed adjustments.

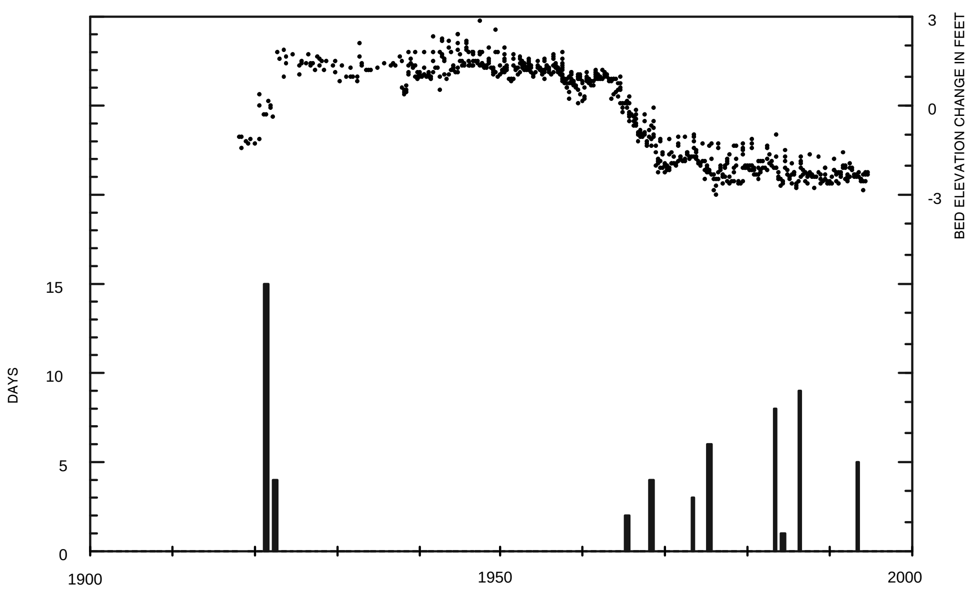



Figure 22. Comparison of minimum streambed elevations to bankfull flow days. This plot shows the MINSBE data along with years that had multiple days in which the daily mean discharge equaled or exceeded the mean annual flood of 1200 ft$^3$/sec.

particular, substantial degradation occurred incrementally over a number of years in response to a range of frequently occurring flows. The degradation did not occur all at once in response to an infrequent large-magnitude flood.

The preceding paragraphs describe relatively simple ways of estimating the discharges responsible for geomorphic adjustability. Greater precision, possible with this data set, involves statistical time series analyses that are beyond the scope of this report. However, one promising avenue of further analysis uses flow duration data. For example, MINSBE plots can be compared with the number of days per year that daily mean flows equaled or exceeded the mean annual flood (figure 22). Figure 22 is a plot of the Ashley Creek data that shows some visual correlations between years of sustained high flows and streambed response; however, a clear pattern is not indicated.

# Detailed Site Characterizations

Detailed site characterizations of the contemporary stream morphology link the historic record to the present-day, serve as additional data points that extend the historic record, and are tools that help extrapolate findings to other stream reaches. More specifically, site characterizations:

- accurately depict the spatial organization of the geomorphic elements;
- can be used to assess the differences between DM locations;
- are valuable in determining which cross-sections to replicate;
- justify assumptions made during the historic record analysis;
- quantify the relative errors associated with the historic record analysis;
- examine the reasonableness of the conclusions drawn from the historic record analysis; and
- provide a familiarity with the site that helps prevent interpretations of the historic record analyses from becoming too abstract.

The central element of a detailed site characterization is a geomorphic map. Other components include cross-sections, longitudinal profiles, and sediment transport studies. Mapping the earth's surface is "essential for an understanding of spatial distributions and relationships" (McKnight 1990), and maps are the primary tool used by geomorphologists. Leopold and Wolman (1957) used detailed maps to quantify stream channel patterns, and Lisle (1986) incorporated detailed channel morphology maps in his assessment of gravel bars in steep, coarse-bedded mountain streams. Detailed channel morphology maps were developed by Keller and Tally (1979) to quantify the impacts of large organic debris on channel geometry, fish habitat, and patterns of erosion and deposition in mountain streams of northern California. In addition, Madej (1984, 1995) mapped the channel in detail to quantify sediment storage and channel stability in a mountain watershed.

Detailed channel morphology maps facilitate contemporary decision-making and with time, become valuable sources of historic data. Most importantly, detailed maps of reference sites provide a means for extrapolating the findings at those sites to other stream reaches. If the geomorphic history and spatial organization of geomorphic elements (as depicted on maps) are understood at a reference site, then these histories can be extrapolated to other reaches that exhibit the same geomorphic organization. While the basic techniques of surveying and other methods of stream channel characterization are well described in Harrelson et al. (1994), techniques of detailed geomorphic mapping are not discussed.

Basic survey techniques using a surveyor's level rely on pace, tape, or indirect measurements of a stadia-rod for horizontal distances, and horizontal angles are plotted by hand. For third- and fourth-order streams, where typical study reaches exceed 1,000 ft, surveying with a theodolite is more efficient. For purposes of detailed mapping, it is necessary to accurately survey a network of permanent and temporary benchmarks that are within 100 ft of each other. The permanent benchmarks are typically the ends of cross-sections, cultural features, and definitive pieces of the gage station. The temporary benchmarks include knick points along the water's edge marked with pin flags or removable rebar, trees, and individual boulders. The distance limitation is necessary because the mapping technique requires that a tape measure be stretched between benchmarks. With an accurately surveyed base map of permanent and temporary benchmarks, detailed geomorphic mapping is conducted in 2 phases. The first phase characterizes the large-scale aspects of the fluvial landscape and the second phase characterizes the finer details.

## Detailed Geomorphic Mapping - Phase I

Phase I mapping delineates the water edges, bars, banks, and associated geomorphic features greater than 15 $ft^2$. In addition, fences, structures, trees, and prominent boulders are mapped for use as benchmarks during phase II mapping. Phase I mapping is best accomplished by a mapper and an assistant. The assistant performs the measurements and the mapper draws the map. First, a 100 ft fiberglass tape measure is stretched tight and fairly level between 2 of the surveyed benchmarks in the field. This is the baseline from which individual points will be measured. A line, representing the stretched tape, is drawn on the map between the points that symbolize the surveyed benchmarks. The mapping begins at one of the benchmarks and continues along the length of the tape to the other benchmark. Thereupon, the fiberglass tape is "leap-frogged" to the next benchmark, and the mapping process continues in this manner all along the reach.

The particular points plotted to draw the map are measured from the stretched tape with a retractable metal tape (1-inch wide for rigidity) extended perpendicular to the fiberglass tape. The mapper takes the free-end of a metal tape and holds it to the point or feature to be measured, taking care to maintain the metal tape fairly level. The assistant slides the other end of the metal tape along the stretched fiberglass until the metal tape is perpendicular to the stretched tape. The assistant first reports the location of the metal tape along the stretched fiberglass tape, and then reports the distance recorded by the metal tape. The mapper similarly scales these distances on the map and plots the point. The mapper is responsible for connecting the dots and drawing the map as each point is measured. Phase I mapping can proceed in a timely fashion along the reach, and the assistant should never be idle for more than one minute while the mapper draws.

### Detailed Geomorphic Mapping - Phase II

Phase II mapping characterizes the geomorphic details of the reach. During this phase, the bars, pools, riffles, prominent boulders, eddies, and the flow pattern of the active channel are mapped. In addition, meso- and microscale topography, vegetation patterns, surficial geology, and high watermarks all along the riparian corridor are drawn on the map. As mapping proceeds, the map is annotated in detail, bank materials are described, and photograph stations are established. The measurement of points for this phase of mapping is typically a combination of pace and compass and solo execution of the 2-person technique described above. Mapping at this detail requires the use of simple symbols and colored pencils to maintain map readability. Figure 23 is an explanation of useful map symbols. Figure 24 is a detailed geomorphic map of Ashley Creek. Phase II mapping requires concentration and objectivity. A goal of this mapping is to define the active floodplain, but all geomorphic surfaces composed of alluvium are mapped. Subsequent analysis of the map, cross-sections, and longitudinal profile projected through the gage, are then used to define the active floodplain and bankfull discharge.

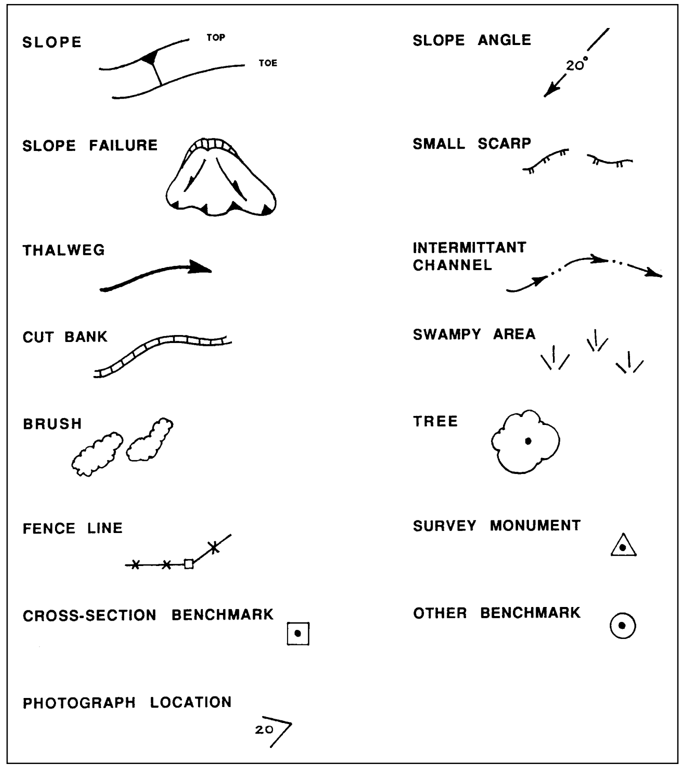



Figure 23. Explanation of map symbols.

## Channel Morphology and Bankfull Discharge

The elevation, stratigraphy, and vegetation characteristics of the geomorphic surfaces are analyzed using the detailed geomorphic map and channel cross-sections (figure 25). The elevations of these surfaces are plotted on the longitudinal profile (figure 26) so that the surfaces can be correlated longitudinally. Theoretically, each geomorphic surface is created by a specific discharge that is part of a particular hydrologic regime (Leopold et. al 1964). By drawing lines on the longitudinal profile that parallel the bankfull water level and intersect the elevations of the different geomorphic surfaces, it is possible to longitudinally correlate these surfaces and realize the average water surface elevations necessary to inundate each surface. When these lines are drawn through a gaging station, their intersection with the staff plate and an examination of the rating relation allow for determination of discharges necessary to inundate, and likely form, the geomorphic surfaces. Once the discharges are known, the recurrence interval curve (figure 5) is used to determine how often the surfaces are inundated. This procedure is

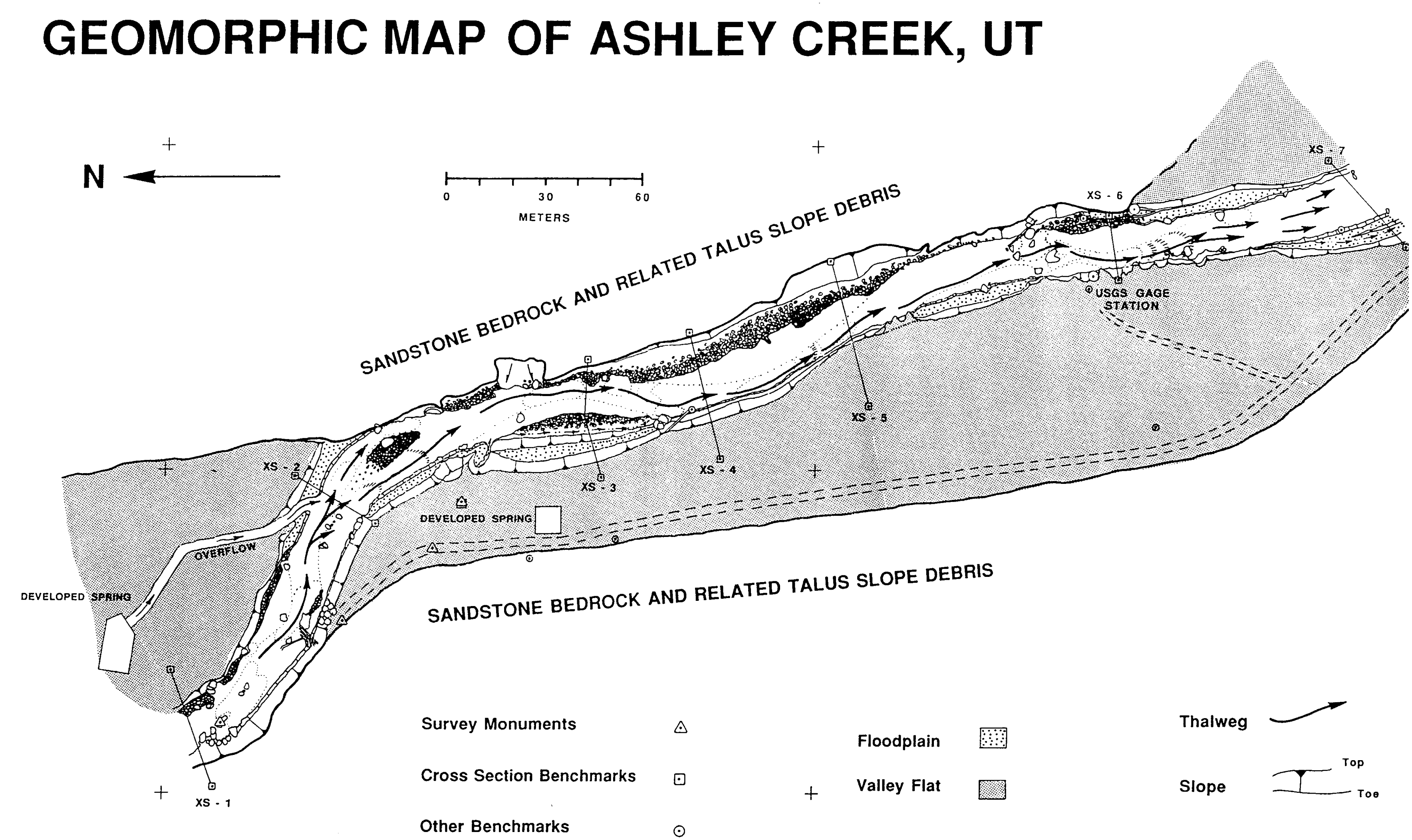
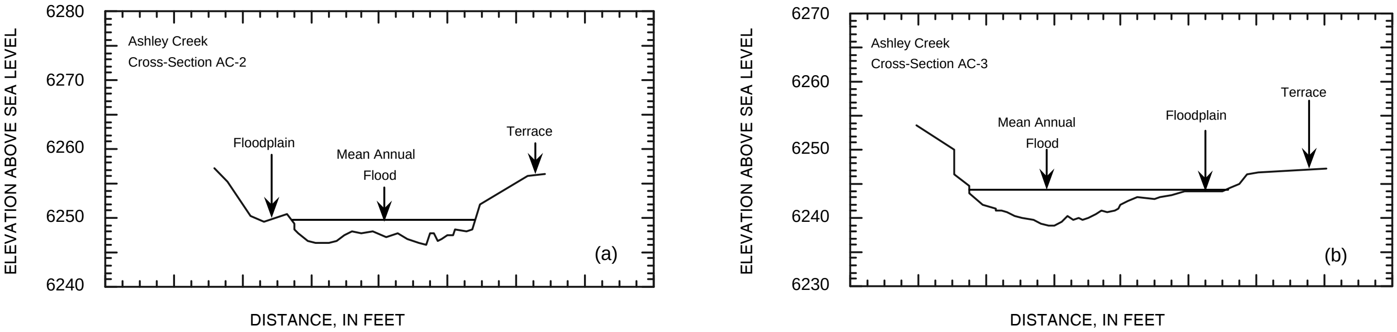



Figure 24. Geomorphic map of Ashley Creek. The active floodplain is inset within the incised channel and is discontinuous.



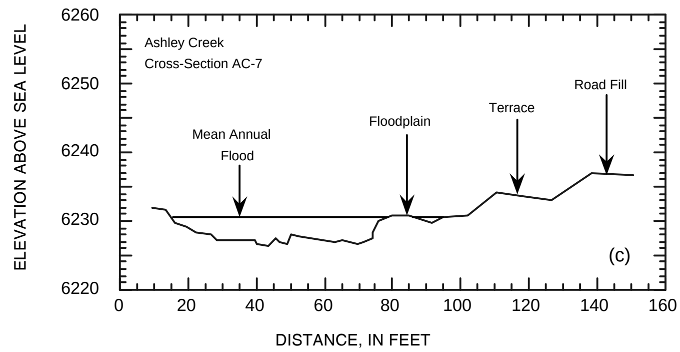




Figure 25. Representative cross-sections of Ashley Creek. Plots (a), (b), and (c) are representative cross sections that show similar alluvial surfaces (active floodplain and terrace), which are longitudinally correlative.

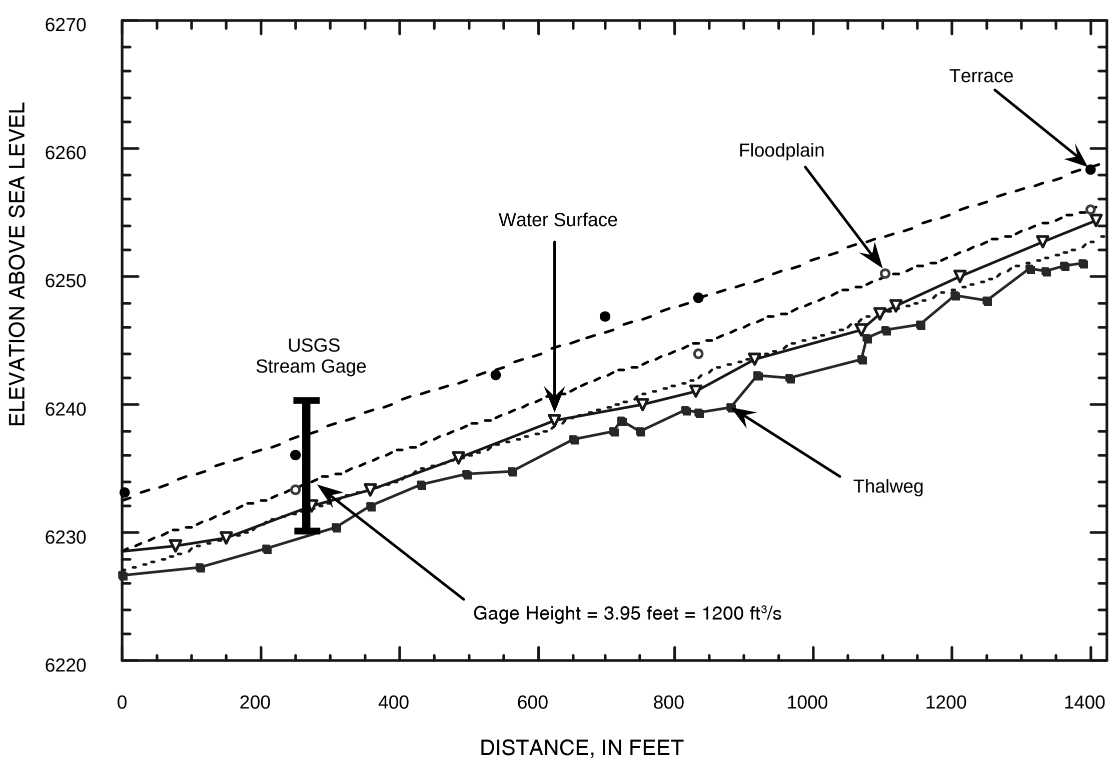



Figure 26. Longitudinal profile of Ashley Creek. This profile shows a longitudinally correlative surface that intersects the gage at 3.95 ft. A gage height of 3.95 ft corresponds to a discharge of ~1200 $ft^3$/sec, which is the mean annual flood with a recurrence interval of 2.3 years. Because the surface is relatively flat, located adjacent to the active channel, and inundated by frequently occurring flows, it is considered to be the active floodplain.

further discussed by Leopold (1994) and Harrelson et al. (1994).

At the Ashley Creek study site, 2 different surfaces were longitudinally correlative (figures 24 and 25). Of particular interest is a prominent surface adjacent to the active channel that is inundated by the mean annual flood. Field observations of newly deposited sand on these surfaces indicate that these surfaces are being constructed by the current hydrologic regime. Therefore, this surface is considered an active floodplain, and its elevation is correlative with the water level coincident with a discharge of 1200 $ft^3$/sec. Consequently, the mean annual flood is representative of bankfull conditions. At the Ashley Creek study site, the active floodplain is small, discontinuous, and comprises less than 4% of the valley floor (figure 24). These findings illuminate the inherent difficulty in identifying the active floodplain of mountain streams, and thus, reinforce the importance of performing detailed site characterizations.

## Management Implications

The methods described in this report were developed to measure historic stream channel changes and better understand fluvial processes in mountainous regions. This report explains how to analyze USGS gaging station records and complete detailed site characterizations. The methods are designed to reconstruct stream channel histories that can then be compared to histories of climate change, stream regulation, and land-use. In turn, these comparisons can be used to link geomorphic adjustments to natural cycles, rare events, and land-use activities. With such linkages, models of channel change can be developed to assist resource managers in understanding the susceptibility of mountain streams to regulation and land use.

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