Cooperative National Park

RESOURCES STUDIES UNIT

SPRING FLOW IN A PORTION
OF GRAND CANYON
NATIONAL PARK, ARIZONA

University of Nevada
Las Vegas, Nevada 89154

Western Region
National Park Service
Dept. of the Interior
San Francisco, CA 94102

COOPERATIVE NATIONAL PARK RESOURCES STUDIES UNIT
University of Nevada/Las Vegas - National Park Service

The National Park Service and the University of Nevada signed a Master Agreement on November 4, 1971 that provided for the establishment and operation of this Unit on the Las Vegas Campus. The Unit, although located in the Department of Biological Sciences, is geared to provide a multidisciplinary approach that utilizes all talents on the University Campus to natural resources studies in areas administered by the National Park Service. Primary attention of this Unit is directed to Death Valley National Monument, California/Nevada; Lake Mead National Recreation Area, Nevada/Arizona; and Joshua Tree National Monument, California.

Through the direction and coordination of the Unit Leader, projects are undertaken in these areas that are designed to provide scientific facts upon which the park managers may make appropriate decisions and formulate and implement effective management action plans. Through close association with faculty members and through guidance of graduate students, a greater awareness of problems and needs of the Service are recognized and academic interests are channelized to participate with the National Park Service in studies of mutual interest and concern.

NOTICE: This document contains information of a preliminary nature, and was prepared primarily on an interim basis. This information is not intended for use in open literature prior to publication by the investigators named unless permission is obtained in writing from the Unit Leader.

COOPERATIVE NATIONAL PARK RESOURCES STUDIES UNIT
UNIVERSITY OF NEVADA, LAS VEGAS
Department of Biological Sciences
Las Vegas, Nevada 89154

Charles L. Douglas, Unit Leader
Senior Research Scientist
National Park Service

SPRING FLOW IN A PORTION OF GRAND CANYON NATIONAL PARK, ARIZONA

David Bruce Goings

June, 1985

NATIONAL PARK SERVICE/UNIVERSITY OF NEVADA, LAS VEGAS

Contribution Number CPSU/UNLV 033/01

SPRING FLOW IN A PORTION
OF GRAND CANYON
NATIONAL PARK,
ARIZONA

By

David Bruce Goings

A thesis submitted in partial fulfillment
of the requirements for the degree of

Master of Science

in

Geology

Department of Geoscience
University of Nevada, Las Vegas
May, 1985

NPS
27JAN1988
/

The thesis of David B. Goings for the degree of Master of Science in Geology is approved.

Chairman, G. William Fiero

Examining Committee Member, John Hess

Examining Committee Member, Frederick Bachhuber

Graduate Faculty Representative, Charles Douglas

Graduate Dean, James Adams

University of Nevada
Las Vegas, Nevada
May, 1985

TABLE OF CONTENTS

ABSTRACT

Hermit, Monument, Salt, and Horn Creeks flow through four side canyons of the Colorado River within the Grand Canyon. They lie just west of Grand Canyon Village on the south side of the canyon. Each of these creeks is fed by at least one spring.

Comparisons of flow at each of these springs for a 14 month period, and precipitation on the south rim show a close correlation. The lag period between recharge at the rim and discharge at the springs is less than one month for Hermit Creek and between one and two months for the other three creeks.

The relative lag times and water chemistry of the springs indicate the length of the flow path to each spring. These suggest a dual source within the area of study.

Two large faults lie in or near the area of study. These are the Hermit Fault, which lies near Hermit Creek, and the Bright Angel Fault, which lies just east of Horn Creek. Both faults trend in a general north-east direction and are accompanied by a wide fracture zone. Ground water flow in the area of study is

largely controlled by these faults which seem to act as hydrologic collector structures and allow the water to move downward from the rim through the impermeable strata below.

The flow at each spring is a combination of waters from two ground water systems. These ground water systems are controlled by the major faults. The water flows through fractures to each spring. The result is a structurally-controlled, interconnected flow system dominating the entire area of study.

MANAGEMENT CONSIDERATIONS

The relative lag times, from recharge to discharge, indicated by this study, reveal potential problems concerning contamination of the groundwater and springs of the Grand Canyon. The short lag times may not be sufficient to allow for natural decontamination of the groundwater. Other potential health hazards have been revealed as a result of delineation of the groundwater flow paths. Although the exact residence time of any particle of water is not known, the relative lag times, between zero and two months, give an approximate period of residence within the system. The actual flow period is probably quite varied from molecule to molecule and may be greater or less than the times stated.

These short flow periods should be cause for concern in reference to the possible contamination of groundwater. Possible sources for contamination include rapidly incorporated fluids such as sewage from Grand Canyon Village, Desert View, Hermit's Rest, and even Tusayan. Of particular concern is the main sewage treatment facility for the Village which lies very near areas as well. However, additional hydrological and bacteriological study are necessary for identification and quantification of problems at specific locations.

The increase in human population of the Grand Canyon, both transient and permanent, has put a strain on the decontaminating abilities of the groundwater systems operating there. The strain and accompanying ill-effects are likely to increase with the increase in human traffic and waste. It is suggested that an effort be made to identify the possible sources of present and future contamination, both on the rim and below. Steps should be taken to evaluate the potential hazards and to eliminate or reduce them. If possible, future sites of contamination should be placed well away from areas of fracture and far enough from the rim of the canyon as to decrease the possibility of inflow to the groundwater systems controlling springs below the rim. Hazardous chemicals and ore piles should be eliminated from the vicinity and decreases in numbers of hikers in sensitive areas may be necessary to control the problems. In some cases it may be necessary to require hikers to deposit waste in hydrologically-isolated, waste collection sites which might be serviced occasionally by helicopter. Extensive microbiological and further hydrological studies would be very helpful in the identification and control of these problems and should be encouraged and assisted by the Park Service.

INTRODUCTION

Lying just west of Grand Canyon Village, Hermit, Monument, Salt, and Horn Creeks drain a portion of the south rim of the Grand Canyon into the Colorado River approximately 5,000 feet below.

The springs that flow within these side canyons lie within drainage basins bounded by the steep walls of the Grand Canyon. The stratigraphy of the canyon is a series of alternating permeable and impermeable strata. The rim of the canyon is a flat plateau dipping away from the gorge on the south side.

It is the purpose of this study to examine the hydrologic environment and understand the system through which these springs operate. The major objectives of the study are to form a hydrograph of the flow at each of the springs and determine the lag time of the ground water flow from recharge to discharge, to gain an understanding of the interrelationships between the flow systems of each spring, and also to determine the extent to which spring flow can be predicted.

PREVIOUS INVESTIGATIONS

There have been many reports on the stratigraphy and structure of the Grand Canyon. The discussions of these topics included here are based mainly on the works of Metzger (1961), Colbert (1974), and Huntoon (1974a and 1974b).

The number of references in the literature concerning the hydrogeology of the Grand Canyon is quite limited. Huntoon (1974a, 1974b, etc.) has written several papers on the hydrology of the karst systems of the north side of the canyon. Metzger (1961) surveyed the water resources on and below the south rim. La Rue (1925) gave a broad overview of the Grand Canyon area and Johnson and Sanderson (1968) compiled data gathered from several sources of spring flow information.

There has been no effort to document the flow of the springs studied in this thesis or the systems operating in this portion of the Grand Canyon prior to this investigation.

PHYSIOGRAPHY

The area of study includes the four side canyons known as Hermit, Monument, Salt, and Horn, which drain the area from the south rim of the Grand Canyon to the Colorado River. All four of these tributary canyons lie to the west of Grand Canyon Village and have a general north-south trend (Figure 1).

The Grand Canyon separates the Colorado Plateau into the Kaibab Plateau (north rim) and the Coconino Plateau (south rim). The altitude of the north rim is approximately 8,000 feet above sea level and averages 1,000 feet higher than the south. The topographic surface slopes to the southwest, toward the canyon on the Kaibab Plateau but away from the canyon on the Coconino Plateau. This accounts for the great difference in rates of erosion on either side of the river and for the corresponding differences in topography. Within the area of study, the Colorado River lies at an elevation between 2,400 feet and 2,350 feet and flows a distance of approximately 5 miles.

A wide platform lies several thousand feet down in the canyon, a result of erosion of the dense and resistant Tapeats Sandstone and the overlying soft

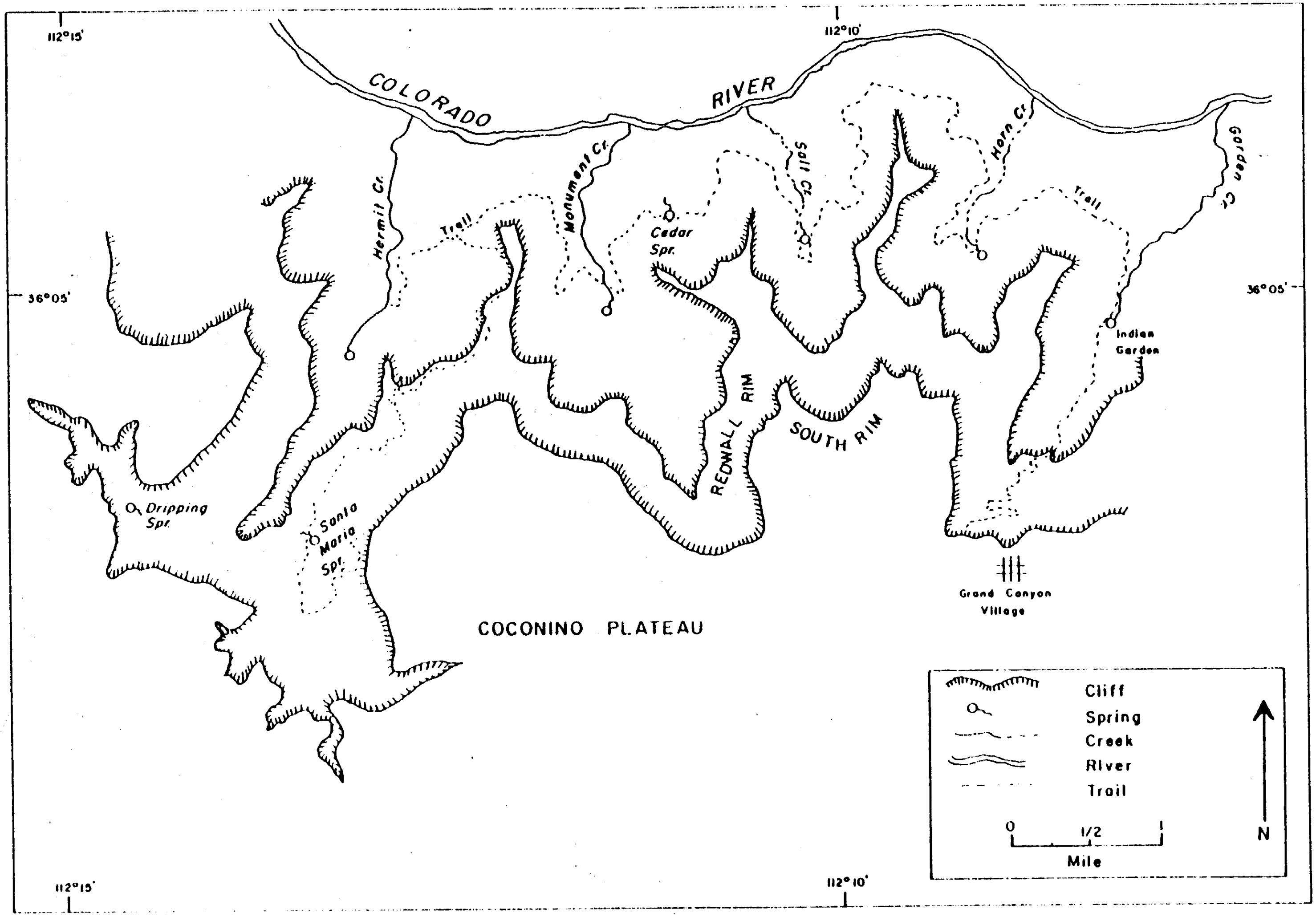


Figure 1.-Map of the area of study

CLIMATE AND VEGETATION

The climate and vegetation of the Grand Canyon vary with elevation. Dense coniferous forests are supported on the north rim by an annual precipitation of up to 30 inches, whereas sparse desert vegetation near the river receives an average of only 9 inches of precipitation per year.

The south rim of the canyon supports forests of pinyon, juniper, and other species (Hamblin and Murphy, 1969). The average annual precipitation at the Grand Canyon Village, is about 15 inches.

The inner canyon is a true desert and exhibits a typical assemblage of southwestern desert flora, including blackbrush, mormon tea, various cacti, and cottonwood trees near perennial streams. Many of these trees were planted by the early settlers of the canyon (Metzger, 1961).

Precipitation in and around the canyon occurs mainly during two wet seasons each year, as winter storms and during the summer thunderstorm season (Green and Sellers, 1964). Snow is common on both rims. Temperatures on the south rim range from a minimum of 20 degrees Fahrenheit to over 80 degrees. Freezing temperatures are rare in the gorge, but summer temperatures commonly exceed 100 degrees Fahrenheit (Thybony, 1980).

STRATIGRAPHY

The stratigraphy of the Grand Canyon has been studied in great detail and thoroughly reported in the literature. This discussion is primarily directed to the water-bearing characteristics of the rocks. Table 1 lists the stratigraphy of the area of study and includes a brief description of the hydrologic characteristics of the strata.

Precambrian Rocks

The Precambrian rocks of the Grand Canyon can be divided into the older Precambrian and the Grand Canyon Series. The older Precambrian consists of the Vishnu Group, the Trinity and Elves Chasm Gneisses, and the Zoroaster plutonic complex. The Vishnu Group is the oldest rock in the canyon and consists of dense gneissic to schistose metasedimentary and mafic meta-igneous rocks (Huntoon, and others, 1980). The Grand Canyon Series can be further divided into the Unkar and Chuar Groups. These are primarily sedimentary rocks that exhibit little metamorphism (Metzger, 1961).

None of these rocks are considered ground water sources. However, small amounts of water do penetrate

Table 1. Grand Canyon Stratigraphy

Age	Unit	Rock type	Thickness	Hydrologic Characteristics
Permian	Kaibab	limestone	300'	permeable (solution, fractures)
unconformity				
"	Toroweap	limestone	280'	" " "
"	Coconino	sandstone	600'	permeable (primary, fractures)
"	Hermit	shale	300'	aquitard (locally permeable)
unconformity				
Permian-Pennsylvanian	Supai	sandstone-shale	950'	" " "
unconformity				
Mississippian	Redwall	limestone	500'	permeable (solution, fractures)
unconformity				
Devonian	Temple Butte	limestone	0-100'	unknown
unconformity				
Cambrian	Muav	limestone	400'	permeable (solution, fractures)
"	Bright Angel	shale	325'	aquiclude
"	Tapeats	sandstone	300'	permeable (bedding, fractures)
unconformity				
Precambrian	Chuar	varied lithology	6610'	unknown
unconformity				
"	Nankoweap	sandstone	330'	unknown
unconformity				
"	Unkar	varied lithology	5321'	unknown
unconformity				
"	Zoroaster	granite to quartz diorite	-	highly impermeable
"	Trinity/ Elves Chasm	gneiss	-	" "
"	Vishnu	metasedimentary/ metaigneous	-	" "

the Vishnu Group to very shallow depths through fractures in some areas. No springs are known to flow from either the Unkar or Chuar Groups. It is thought, however, that the buried hills of the Shinumo Quartzite may affect the movement of water through overlying Cambrian rocks (Metzger, 1961).

Paleozoic Rocks

The Paleozoic strata of the Grand Canyon have been some of the most studied rocks on earth. These studies form the basis of many of the fundamental concepts of geological thinking today. Such names as John Wesley Powell, G. K. Gilbert, C. D. Walcott, and C. E. Dutton have been associated with investigations of these rocks.

The names of the formations, listed in ascending order, are as follows: The Tapeats Sandstone, the Bright Angel Shale, and Muav Limestone of the Tonto Group; the Temple Butte Limestone; the Redwall Limestone; the Supai Group; the Hermit Shale; the Coconino Sandstone; the Toroweap Formation; and the Kaibab Limestone.

The Tonto Group consists of three Middle Cambrian formations, Tapeats, Bright Angel, and Muav, which lie unconformably over the Unkar Group to the east of Grandview Point and unconformably over the older

Precambrian gneisses of the Vishnu Group and others to the west (Metzger, 1961). These formations have gradational contacts and exhibit intertonguing relationships to one another. They can, however, be recognized as individual units throughout the region (McKee, 1974).

The Tapeats Sandstone is a coarse-grained, cross-bedded sand with conglomeratic lenses containing rounded pebbles. It is up to 300 feet thick and forms sheer cliffs, varying in color from dark gray to cream-colored (McKee, 1974).

Little water penetrates the Bright Angel Shale except where there are extensive fractures. Ground water can move through these fractures into the underlying Tapeats Sandstone. In some areas the water exits the Tapeats through bedding planes. Two examples of these Tapeats springs are within the area of study, namely Monument and Salt Creeks. Some small seeps also issue from the Tapeats at Hermit Creek. At Horn Creek, the flow emanates from the gradational contact of the Tapeats and Bright Angel Shale.

An additional feature unique to the springs associated with the Tapeats is the occurrence of stalactites and stalagmites at seeps issuing from the walls of the Tapeats narrows (Metzger, 1961). The Tapeats seep in Monument Creek occurs near the bottom of the formation. Here slender stalactites are up to a foot long. They are white in color and are hollow, allowing water to flow through them. They are primarily composed of halite. Evaporite deposits are quite common near creek beds and seeps in the canyon. Metzger (1961) cites an analysis of crystals found near one of the seeps as being halite. Sulfate and chloride ion have been found in high concentrations by the author in the water below the occurrence of these seeps.

The Bright Angel Shale is predominantly a shaly, green mudstone with some fine-grained sandstone and limestone beds. The color is quite varied, ranging from greens to dark browns to purple. The formation reaches a thickness of 325 feet at the type locality (Metzger, 1961).

Because of its nature as an aquiclude, the Bright Angel Shale may be the most important formation in the Grand Canyon. Nearly all of the water percolating downward through the overlying beds is stopped by this layer. In contrast to the other relatively impermeable strata of the canyon, faulting does not cause secondary porosity in the Bright Angel Shale. These micaceous shales are pulverized along fault planes and form an impermeable barrier to ground water flow (Huntoon, (1974a).

The Muav Limestone consists of mottled limestone and dolomite, interbedded with thin layers of green shaly mudstone. It weathers to form blocky cliffs or steep slopes. This formation is approximately 400 feet thick (Metzger, 1961).

Solution of the carbonates has allowed the formation of channels through the rock, promoting rapid water flow (Metzger, 1961). The combination of the excellent permeability and the confining effect of the underlying Bright Angel Shale account for the number of springs that issue from the Muav. Most of the springs on the south side of the river flow from this layer.

The Devonian Temple Butte Limestone lies unconformably over the Cambrian Muav Limestone. The Temple Butte occurs primarily as local and discontinuous channel fill deposits. In the area of study, outcrops of this formation have a thickness of less than 100 feet (McKee, 1974). The formation is composed of thin fine-grained sandstone layers grading into calcareous sand and limestone (Metzger, 1961). It is purple in color.

No springs flow from the Temple Butte Limestone and it is not considered of importance in the flow of ground water in the canyon (Metzger, 1961).

The Mississippian Redwall Limestone is one of the most obvious of all the strata in the Grand Canyon. The sheer, red cliffs, more than 500 feet thick, are immediately recognizable. It rests unconformably over the Temple Butte Limestone, wherever present, and elsewhere over the Muav Limestone. The Redwall is composed of a thickly-bedded gray limestone, stained red by the overlying Supai Group (Metzger, 1961).

The carbonates of the Redwall Limestone are characterized by the presence of solution channels, permitting the rapid transmission of water (Huntoon, 1974a). On the north rim, these solution channels are part of complex and widespread karst systems that drain the Kaibab Plateau (Huntoon, 1974a). Some of the largest springs in the Grand Canyon flow from these systems. Such springs as Thunder Spring and Cheyava Falls have large orifices high in the Redwall from which water can actually shoot out with tremendous force. Springs flowing from the Redwall on the south side, however, are fed by waters collected into, and flowing through, large faults and associated fractures (Metzger, 1961) rather than karst systems and the resultant flow is less dramatic.

The Supai Group consists of the Pennsylvanian Wescogame, Manakacha, and Watahomigi Formations and the Permian Esplanade Sandstone (Huntoon, and others, 1980). These beds are separated from the Redwall Limestone by an unconformity (McKee, 1974). The Supai Group is primarily interbedded siltstone and fine-grained sandstone. The basal unit consists mainly of red shales and gray limestone. Nearly the entire outcropping area has been stained red by iron oxide from the siltstones. The weathering pattern is a blocky cliff-slope form of approximately 950 feet in thickness (Metzger, 1961).

The siltstones and sandstones tend to act as aquitards. Faults and joints, however, allow the downward percolation of water (Metzger, 1961). Several small seeps appear at the top of the more impermeable layers in some areas. Within the Hermit Basin, Santa Maria Spring flows at a rate of approximately one-half gallon per minute. Also in the Hermit Basin, Four-Mile Spring (still shown on some maps) flowed from the Supai but appears to have been covered by a rockslide (J. H. Butchart, 1985, personal communication). Informal reports to the Park Service have stated that Four-Mile Spring has reappeared and is flowing once again over the trail. These reports have not been investigated and may be inaccurate. This newly reported flow may be an unrelated seep from the Supai.

The Permian Hermit Shale unconformably overlies the Supai Group (Metzger, 1961). The Hermit is a slope-forming red, sandy shale and fine-grained sandstone. Its thickness is about 300 feet in the area of study (Metzger, 1961).

The clay and silt content of the Hermit Shale causes it to retard the movement of ground water and form small seeps at the base of the overlying Coconino Sandstone. As in the case of the Supai Group, fractures in the Hermit Shale allow the downward movement of water.

Lying conformably over the Hermit Shale is the Coconino Sandstone, also of Permian age. The Coconino is a fine- to medium-grained quartz arenite, yellowish to white in color. It stands as a vertical cliff of 600 feet (Metzger, 1961).

The Coconino is relatively permeable, with local variations depending upon the degree of cementation and fracturing. Springs occur, in some areas, at the bottom of the formation due to the confining nature of the underlying Hermit Shale.

The Permian Toroweap Formation is a massive, light-colored limestone that lies conformably over the Coconino. The Toroweap is 280 feet thick and forms a blocky cliff (Metzger, 1961).

According to Metzger (1961) the water-bearing properties of the Toroweap are very similar to the Coconino. No springs flow from the Toroweap and it does not retard the precipitation of water through it.

The Permian Kaibab Limestone is a sandy dolomitic limestone to calcareous sandstone in the area of study (McKee, 1974). Chert is fairly common and the color ranges from yellow-gray to light gray. The 300 foot thick formation (Metzger, 1961) weathers to a blocky cliff. It lies unconformably over the Toroweap Formation.

A large area of the Coconino and Kaibab Plateaus is capped by the Kaibab Limestone. It is important hydrologically since it is quite permeable and allows infiltration. Most of the water that falls as precipitation on the plateaus is, however, lost to evaporation and transpiration before entering the deeper strata. Few springs issue from the formation.

STRUCTURE

The most important structural control to the movement of ground water is the regional dip of the Grand Canyon area, including both the Kaibab and Coconino Plateaus. This dip is approximately 1 to 2 degrees in a southwest direction (Huntoon, and others, 1980). It is this dip that causes the waters of the area to flow away from the rim on the Coconino Plateau and toward the river on the Kaibab Plateau. This results in the abundance of springs and creeks on the north side and their relative scarcity on the south. It has also had a great effect on the relative sizes of the side canyons on either side of the river. The greater southwestward runoff of the north side results in side canyons 2 or 3 times the size of their southern counterparts.

The secondary structure of the Grand Canyon is dominated by two major trends imposed upon the gently dipping Paleozoic strata and the underlying, intensely deformed Precambrian rocks. These trends consist of a group of northeast trending faults of Miocene or Pliocene age and a group of north trending faults and monoclines, which are also Miocene or Pliocene in age

(Huntoon, 1974b). Each of these imposes some degree of control over the flow of ground water in the area.

Table 2 is a partial list of springs and creeks along the 75 mile Tonto Trail and the structural control for the flow of ground water to these springs. It should be noted, however, that this table is based upon the assumption that the major portion of the flow to springs along the south rim is controlled by structure, which may not be true in all cases.

Huntoon (1974b) characterized the northeast trending group of faults as being of "high-angle, normal type". He also states that many of the offsets on the minor faults of this type tend to be reduced in the upper strata of the Paleozoic section. He places the earliest movement in this system somewhere in the Miocene or Pliocene and indicates that this northeast trending system postdates the north trending structural group.

The general effect on ground water flow imposed by this group of structures is to act as conduits for the flow of water. These faults are very important in the movement of water through the aquitards of the Paleozoic. Huntoon (1977) cites faults as being the major control of ground water flow to several large springs in the western Grand Canyon.

Faulting causes the formation of zones of

Table 2. South-side Springs and Associated Structures*

Name of Spring	Associated Structure			
	North trend fault	North trend monocline	North-east fault	High-angle fault
Garnet Creek				X
Bass Canyon			X	
Serpentine Canyon	X (?)			
Ruby Canyon	(no apparent structure)			
Turquoise Canyon	X			
Sapphire Canyon	X			
Slate Creek		X	X	
Boucher Creek	X	X		
Dripping Spring		X		
Santa Maria Spring			X	
HERMIT CREEK		X	X	
MONUMENT CREEK				X
Cedar Spring	(no apparent structure)			
SALT CREEK	(no apparent structure)			
HORN CREEK				X
Bright Angel Creek			X	
Pipe Spring				X
Burro Spring				X
Lonetree Canyon		X		
Boulder Creek		X		
Grapevine Creek		X	X	
Cottonwood Creek		X	X	
Miner's Spring		X		X
Hance Creek		X		X
Red Canyon			X	X

* (Structural information derived from Huntoon, and others, 1980)

permeability. Major faults are commonly composed of many smaller parallel faults, joint sets, pulverized zones, and other fractures that may extend for great distances away from the main fault. Permeabilities within these zones may be increased by factors of 10, 100, or more (Huntoon, 1974a). These fractures, faults, and joints are the conduits through which water bypasses impermeable shales and travels to the springs.

Affecting the area of study are two northeast trending faults. These are: (1) The Bright Angel Fault (lying near Garden Creek), and (2) the Hermit Fault (lying just east of Hermit Creek), (Figure 2). The Bright Angel Fault is a major fault extending completely across the Grand Canyon. It is the structural control for the location of Bright Angel Canyon and Garden Creek. It has a displacement of 200 feet near the south rim and is downthrown to the east (Huntoon, 1974b). The Hermit Fault is considered a minor structure, exhibiting only 30 feet of throw. It extends from the Colorado River up through the Hermit Basin, and southwestward on the Coconino Plateau, and it is downthrown to the west (Huntoon, and others, 1980). The main fault is bounded by parallel minor faults with throws as small as a few inches (Metzger, 1961). These two faults appear to act as the main hydrologic collecting structures for the area of study.

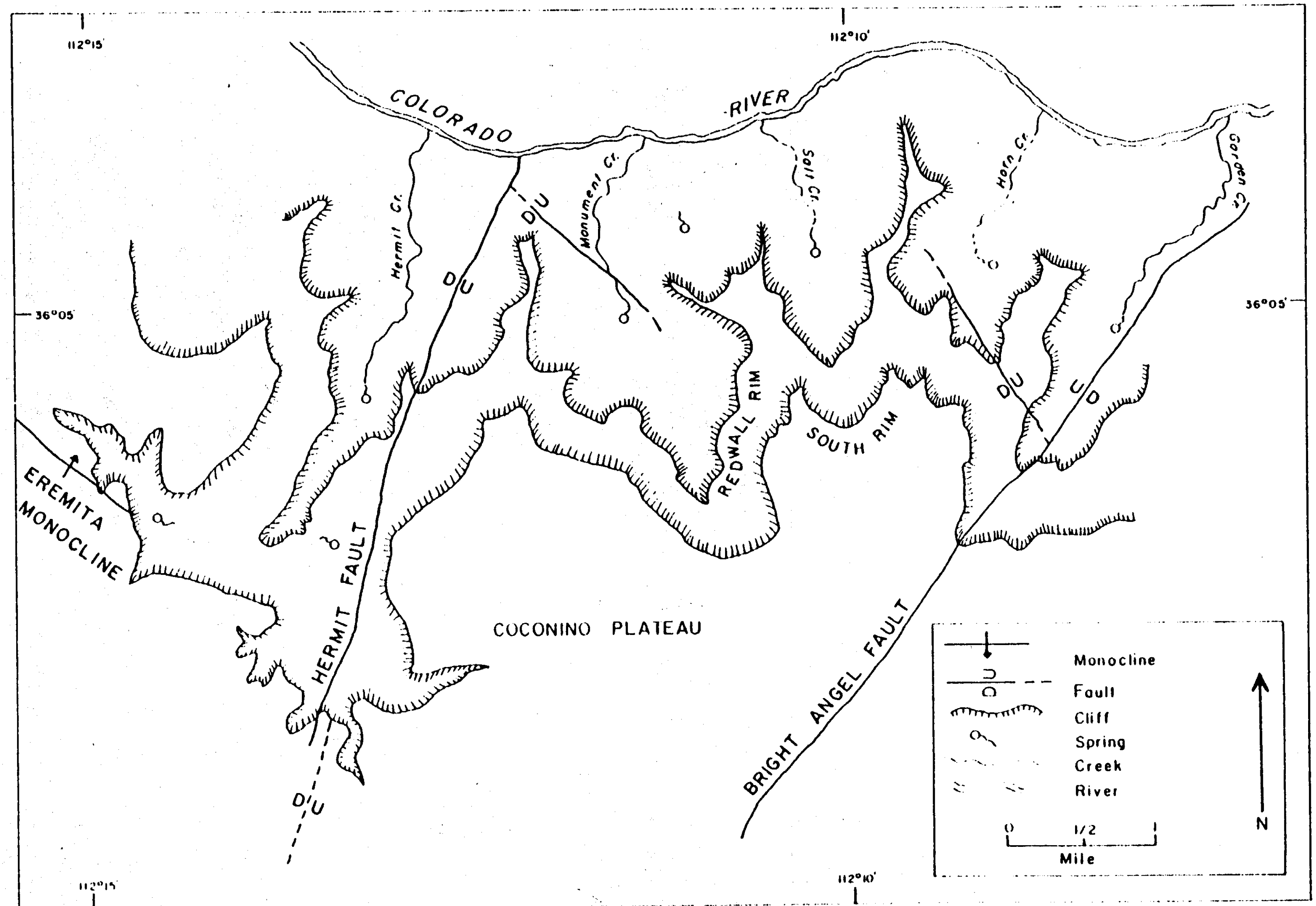


Figure 2.-Structural map of the area of study (adapted from Huntoon, and others, 1980).

The north trending structures of the Grand Canyon are of two types, extensive monoclinal flexures and associated normal faults (Huntoon, 1974b). The flexures grade into reverse faults that overlie faults of Precambrian age. These monoclines generally dip to the east (Huntoon, 1974b). Huntoon (1974b) also states that the associated normal faults were produced after the Miocene-Pliocene aged monoclines.

The monoclinal flexures are more important, hydrogeologically, on the south rim than on the north. The regional dip away from the canyon on the Coconino Plateau is negated, locally, by the effects of these folds. Stratigraphic dip of most of these folds is eastward. Where the fold reaches the south rim, the result is a dip toward the canyon. This results in ground water flow into the canyon rather than away.

Only one of these north trending structures occurs within the area of study. It is the Eremita Monocline and it lies just at the eastern tip of the Hermit Basin (Figure 2). It trends northwest (due to the sinuosity of the flexure) and extends for 3 miles to the west (Huntoon, and others, 1980). This fold displaces strata up to 100 feet and causes the beds near the rim to be tilted at approximately 5 degrees northeast toward the river (Huntoon, and others, 1980). According to Huntoon (1974b), this monocline is a segment of a fold that continues to the northwest.

This small tilting of the rocks near the rim allows percolating water to flow toward the canyon and to exit within Hermit Basin via Dripping Springs, which issues from the base of the Coconino. Some of the northward flow is captured by the Boucher Basin, just west of Hermit Creek, which may derive the greatest portion of its flow from the structural control of this monocline.

Another structural control of ground water of the Grand Canyon is high-angle gravity faults. Huntoon (1974b) describes these numerous structures as nearly vertical normal faults which commonly extend for less than 2 miles. They occur between buttes and the rim of the canyon, and exhibit displacements up to 50 feet. These are thought to be formed along preexisting joints and fractures.

Two such faults lie within the area of study. Both are northwest trending and extend for less than two miles. The first extends from near the southernmost end of the Hermit Fault to the east slope of Monument Creek (Figure 2). It is downthrown to the south with 20 feet of throw (Huntoon, and others, 1980). The other extends from the Bright Angel Fault, just south of Grand Canyon Village, to the west arm of Horn Creek (Figure 2). This fault displaces the strata only 10 feet, also downthrowing the southern block (Huntoon, and others, 1980). As with other faults, the minor faults are important to the movement of water, in that they create zones of permeability through which the water can pass.

METHODS OF INVESTIGATION AND DATA COLLECTED

The remoteness of the area of study was critical in determining the extent and type of methods of investigation to be used. Lying approximately 3,400 feet below the south rim, the springs were accessible only on foot by means of a 25 mile hike.

The area was visited at least once a month for 14 months beginning in March 1983 and continuing through April 1984. The monthly visits consisted of flow measurements, sample collections, and reconnaissance of the local geology and hydrology. In addition to the regular visits, occasional hydrological and geological reconnaissance trips were made before, during and after the period of study. These trips covered much of the Grand Canyon and most of the major springs therein.

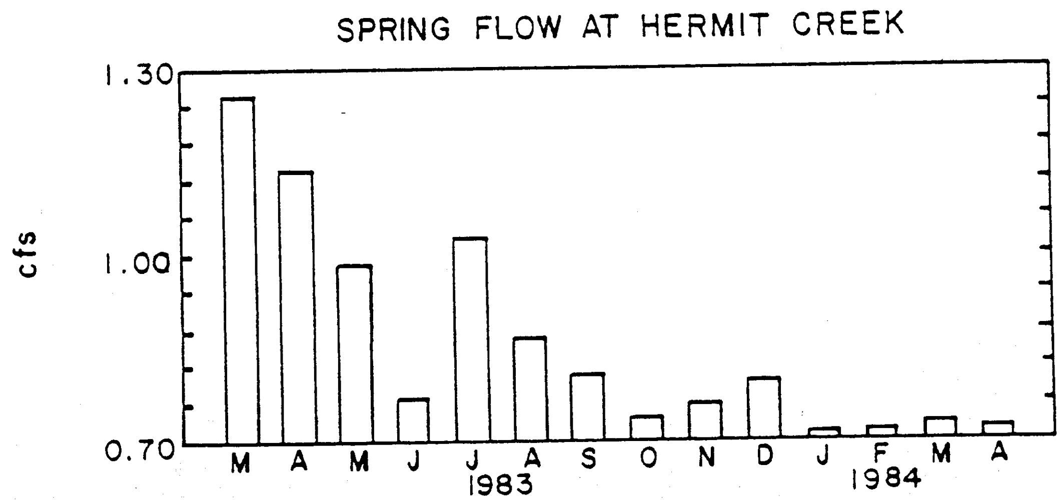
Flow measurements were conducted using a variety of methods. These were often duplicated using two methods in order to allow for comparison and correction of data at a later date. All measurements and samplings were done as near the main spring orifices as possible. Also, other references, such as Johnson and Sanderson (1968), were consulted in an effort to check the accuracy of the measurements.

Measurements at Hermit Creek were conducted using a Pigmy current meter and by measuring average velocity and cross-sectional area of the stream. At Monument Creek, data were collected using a 90 degree V-notch weir and the average velocity and cross-sectional area method. Salt and Horn Creeks' spring flow data were obtained by measuring the volume of water flowing into a container per unit time. Horn Creek was also measured using the 90 degree V-notch weir (Table 3 and Figure 3).

Table 3. Spring Flow in the Area of Study

Month/Year	Spring Flow (cfs)			
	Hermit	Monument	Salt	Horn
3/83	1.26	0.44	0.011	0.024
4/83	1.14	0.37	0.010	0.023
5/83	0.99	0.26	0.009	0.017
6/83	0.77	0.22	0.007	0.010
7/83	1.03	0.11	0.003	0.004
8/83	0.87	0.19	0.004	0.010
9/83	0.81	0.10	0.002	0.009
10/83	0.74	0.15	0.003	0.013
11/83	0.76	0.15	0.002	0.007
12/83	0.80	0.20	0.004	0.009
1/84	0.71	0.22	0.005	0.012
2/84	0.72	0.14	0.002	0.009
3/84	0.73	0.18	0.002	0.012
4/84	0.72	0.20	0.002	0.008

Samples were taken twice at each spring for gross chemical analyses. The first samples were taken in May 1983 at all springs. Samples were also collected in



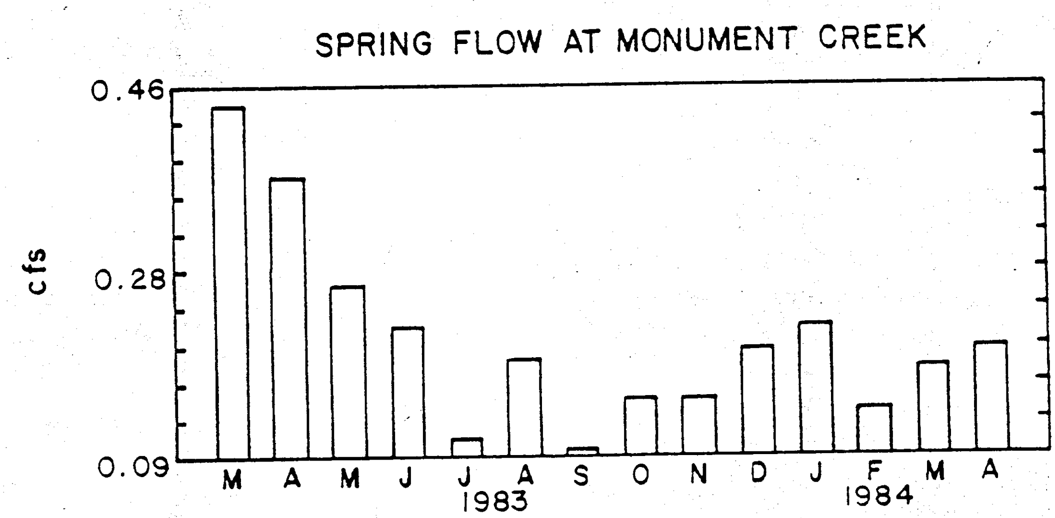


Figure 3.-Spring flow at studied creeks.

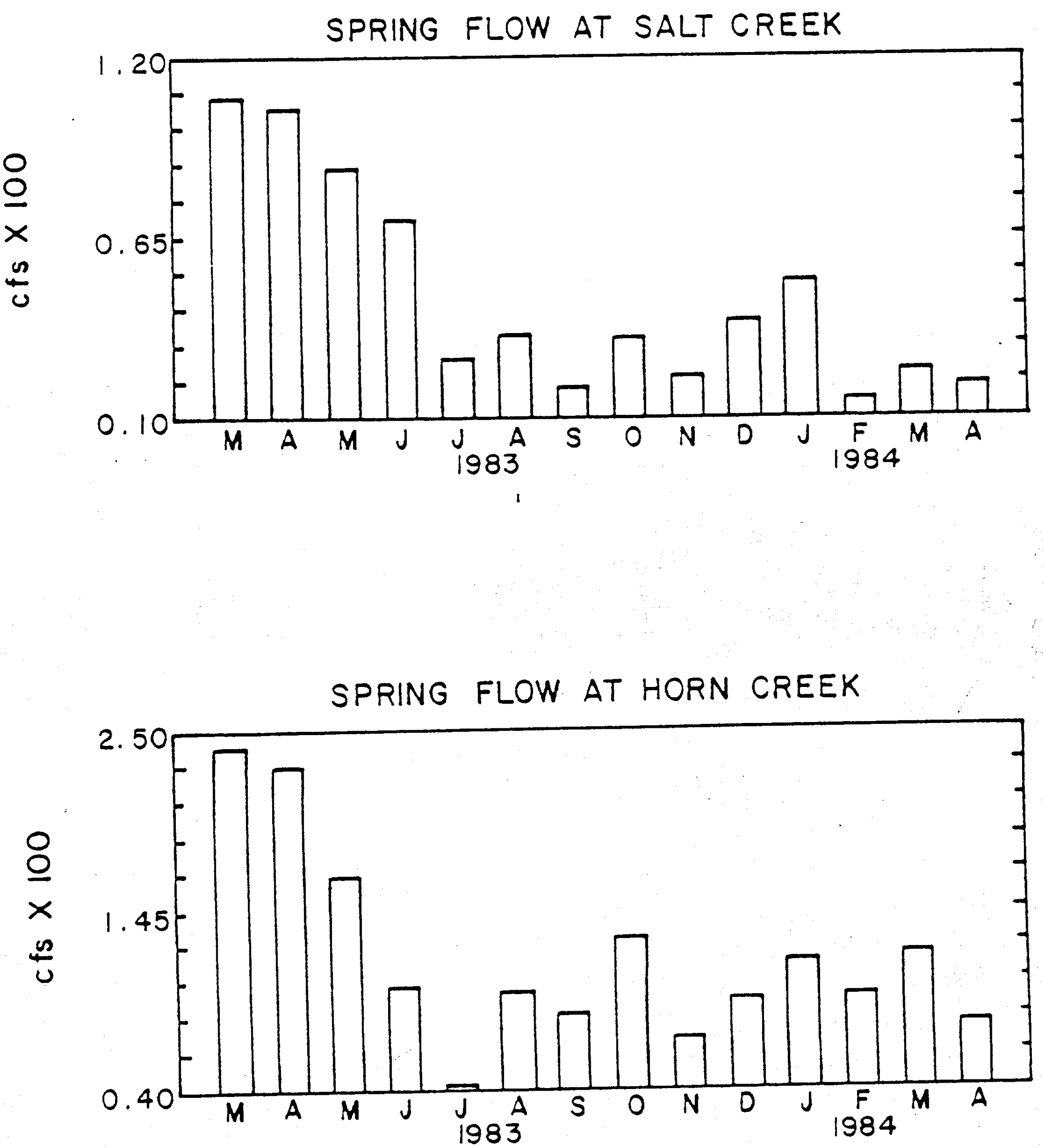


Figure 3.-Continued.

June 1983 at Horn and Salt Creeks, and in October 1983 at Monument and Hermit Creeks. The choices for sampling dates were based on the projected estimates of high and low flow periods. These were primarily based upon flow records of Bright Angel Creek (U. S. Geol. Survey, issued annually), which showed a high flow period in May and a low in October. Collections at Salt and Horn Creeks were performed in June due to the possibility of those springs drying, which never occurred during the period of study. Results of these analyses are shown in Table 4 and Figure 4.

Rough calculations of the basin sizes of each of the springs were made using base flow figures of the Colorado River at Compact Point (near Lee's Ferry) and near Grand Canyon, Arizona (U. S. Geol. Survey, issued annually). Flow figures for those years with similar precipitation records to 1983 (prior to the construction of Glen Canyon Dam) were used to determine the average inflow to the Colorado River, per unit area, in this region. This figure, approximately 0.021 cfs/sq. mi., was then used to divide the base flow figures obtained at each of the springs during the year of measurement. The result is minimum drainage area required to produce the flow observed at each of the springs. Metzger (1961), cites a figure of 11 square miles of surface drainage for Hermit Creek (10 square

Table 4. Chemistry of Studied Spring Waters

Name of Spring	Hermit	Hermit	Monu-ment	Monu-ment	Salt	Salt	Horn	Horn
Collection date (1983)	5/20	10/14	5/21	10/15	5/21	6/25	5/21	6/25
Discharge (cfs)	0.98	0.74	0.26	0.15	0.009	0.003	0.017	0.004
Temperature (deg. F)	61	61	60	62	61	63	61	63
pH (lab)	8.48	7.82	8.24	7.93	8.23	8.26	8.19	7.97
TDS (by summation)	326.3	275.2	915.2	822.8	1084.7	1082.6	819.8	778.2
Sp. Conductivity (micromhos/cm @ 25 deg. C)	574.0	499.0	1470.0	1380.0	1510.0	1490.0	1180.0	1150.0
Constituents (ppm)								
HCO_3	240.0	203.0	269.0	216.0	287.0	263.0	339.0	329.0
Cl	38.2	35.9	176.0	218.0	39.2	41.0	43.1	48.2
SO_4	55.6	39.4	314.0	223.0	592.0	601.0	366.0	318.0
Na	23.3	22.3	95.7	114.0	43.3	45.8	38.5	40.8
K	3.9	4.0	11.7	11.9	17.7	19.0	14.8	16.4
Ca	37.1	27.7	88.0	64.2	108.0	97.3	81.1	77.7
Mg	38.2	34.4	84.3	71.7	130.0	136.0	92.8	95.6
SiO_2	10.0	10.0	11.0	12.0	11.0	11.0	14.0	17.0
Anions (epm)	6.42	5.19	15.93	14.33	18.18	17.98	14.39	13.37
Cations (epm)	6.11	5.28	15.79	14.36	18.42	18.52	13.73	13.93
Epm balance	0.98	1.05	1.01	1.00	0.99	0.97	1.05	0.96

(Analyses performed by Desert Research Institute, Reno, Nevada)

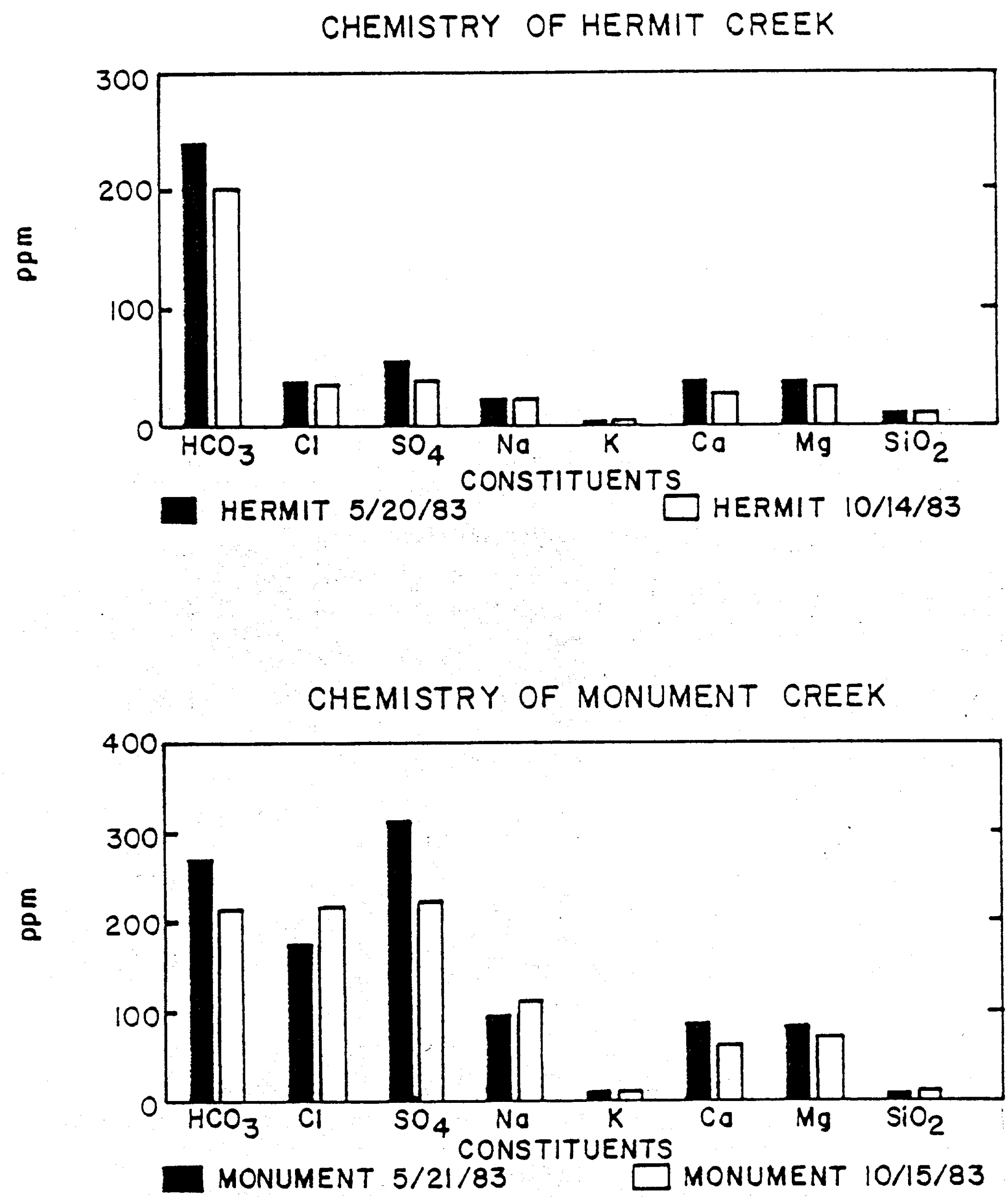
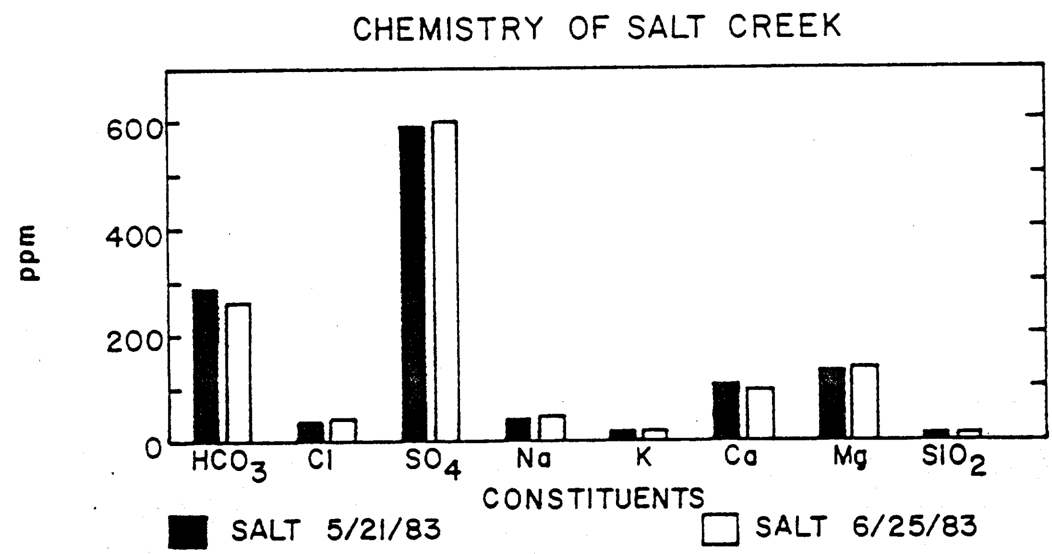


Figure 4.-Chemistry of water from studied creeks.



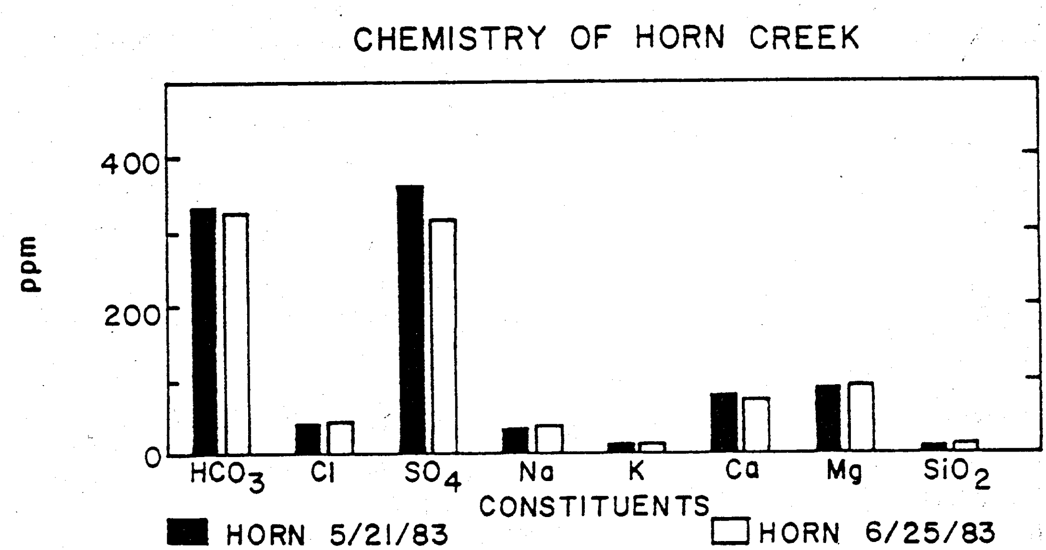


Figure 4.-Continued

miles above its lowest major contributing spring). This figure does not correspond to the figure of approximately 34 square miles obtained for Hermit Creek using the technique described above. This may indicate that surface drainage basin and ground water basin divides do not correspond, at least in this area. The figures obtained for the other ground water basins are as follows: Monument Creek - 5 square miles; Salt Creek - .1 square miles; Horn Creek - .2 square miles. The total for the four creeks is approximately 39 square miles.

Finally, precipitation data were obtained through the U. S. Department of Commerce (N.O.A.A.), from their Hourly Precipitation Data publication (issued monthly). This information is listed in Table 5 and shown graphically in Figure 5.

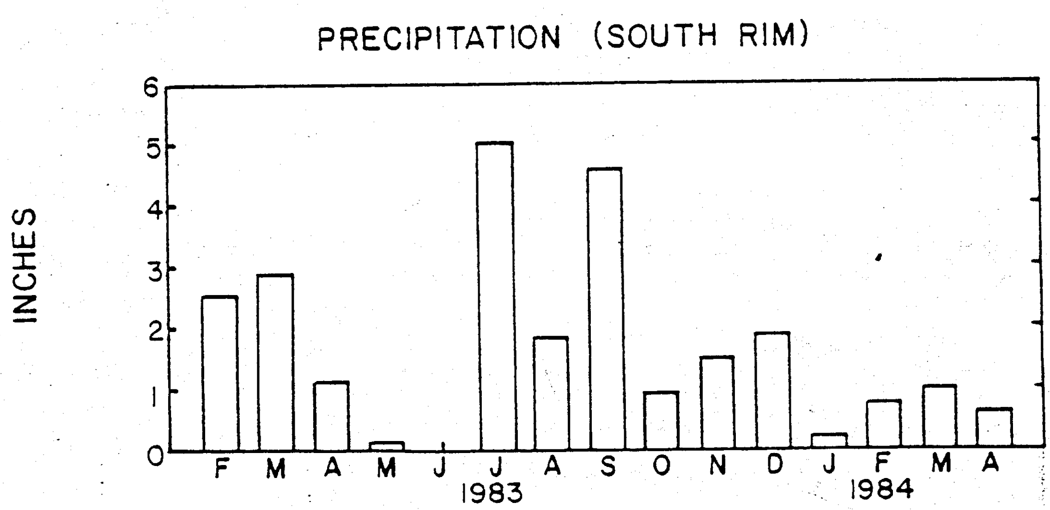


Figure 5.-Precipitation at the south rim.

Table 5. Precipitation on the South Rim*

Month/Year	Precipitation (inches)	Monthly Averages (1900-1983)
2/83	2.54	1.53 F
3/83	2.87	1.37 M
4/83	1.15	0.92 A
5/83	0.16	0.65 M
6/83	Trace	0.46 J
7/83	5.04	1.87 J
8/83	1.84	2.28 A
9/83	4.58	1.50 S
10/83	0.92	1.21 O
11/83	1.48	0.95 N
12/83	1.87	1.60 D
1/84	0.24	1.35 J
2/84	0.78	
3/84	1.02	
4/84	0.61	
Total	25.10	
Yearly Average (1900-1983)		15.69

* (Precipitation data from U. S. Dept. of Commerce)

DISCUSSION

The hydrographs developed during the period of study permit a comparison of flow patterns at the springs with precipitation (recharge) at the rim. It should be noted, however, that data were gathered during an abnormally wet period. The author does not believe this invalidates the analyses and conclusions presented herein. A data base consisting of several consecutive years of closely spaced measurements and sample collections, encompassing both dry and wet periods, may be necessary for complete and detailed understanding of the flow system.

Figure 6 shows spring flow plotted with precipitation at the rim for the same period. Hermit Creek's flow pattern shows a direct temporal relationship with precipitation. Monument, Salt, and Horn Creeks', however, do not. Figure 7 illustrates the hydrographs of the springs plotted with precipitation. In these graphs, the spring flow tracings for Monument, Salt, and Horn are shifted one month to the left. Hermit Creek's hydrograph, (Figure 7) is not shifted. When shifted, these tracings match the trends of the precipitation very closely. The lag time from precipitation

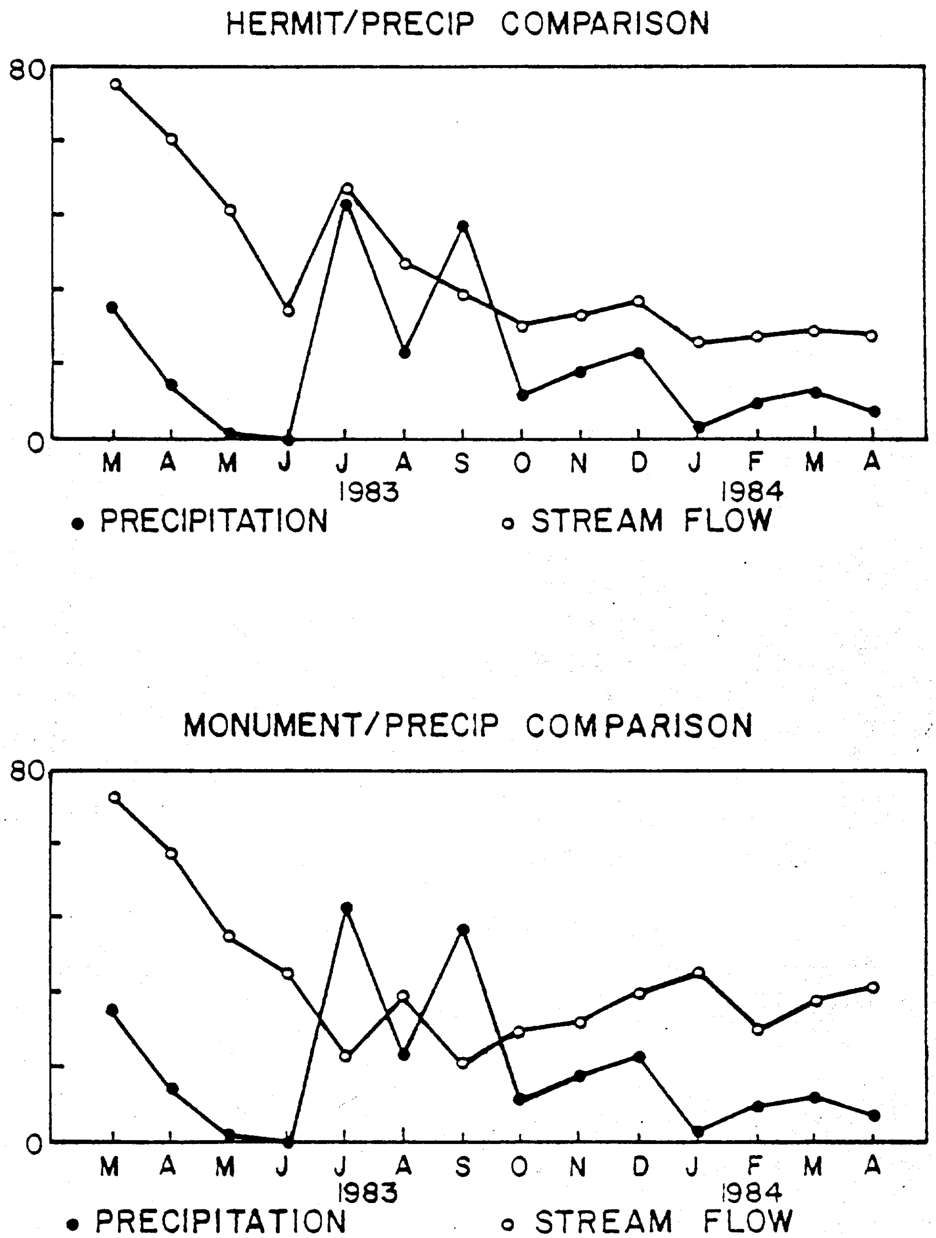
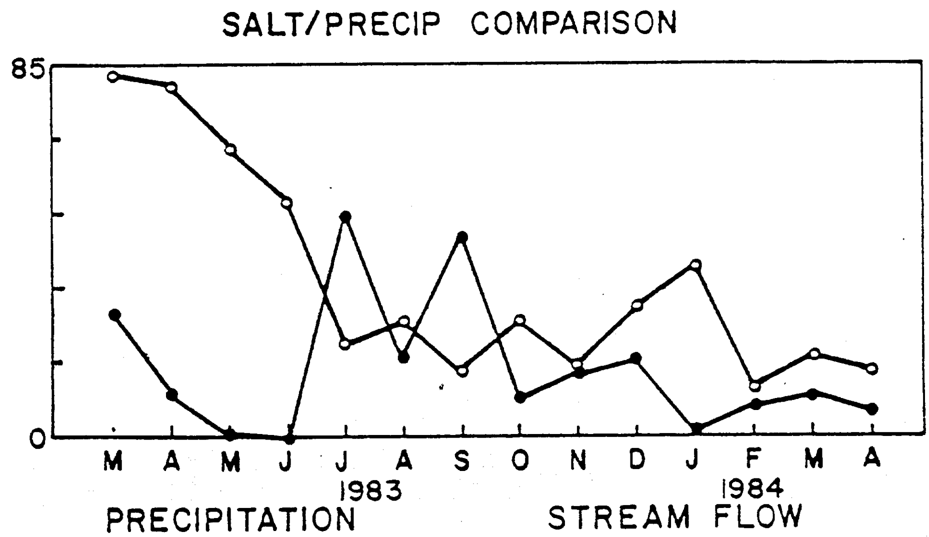


Figure 6.-Comparisons of precipitation and spring flow during period of study



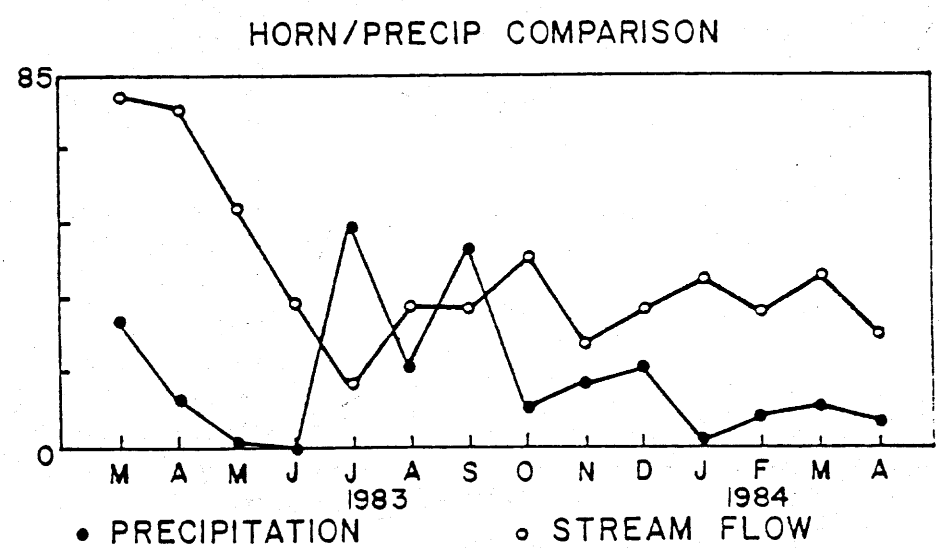
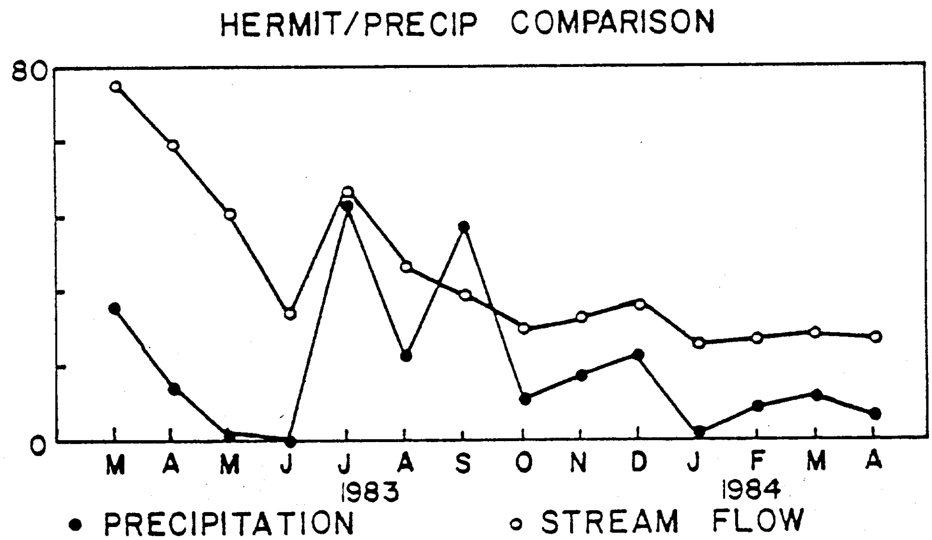


Figure 6.-Continued.



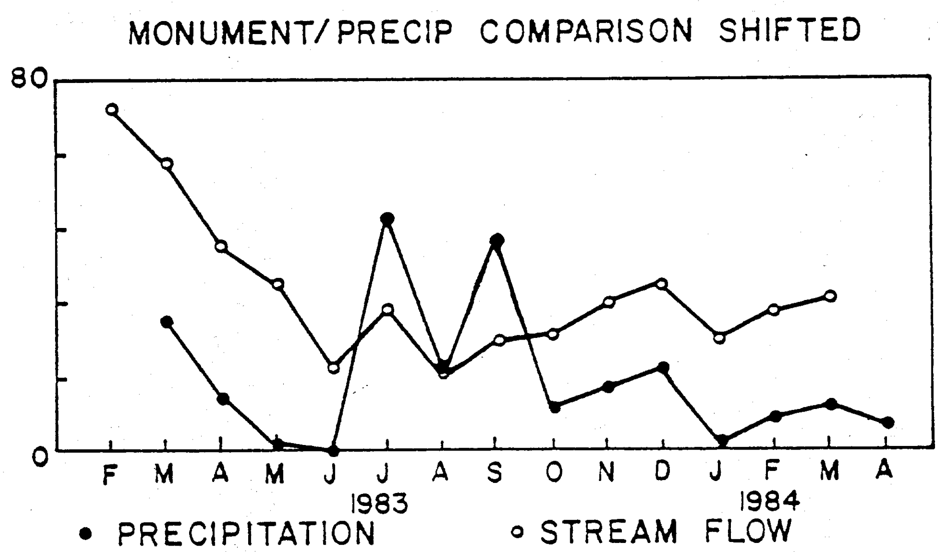
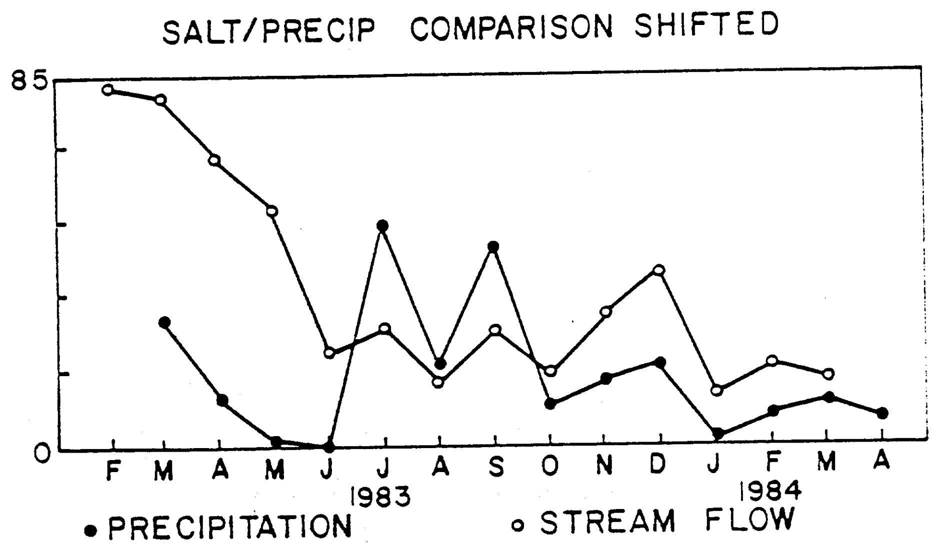


Figure 7.-Adjusted comparisons of precipitation and spring flow during period of study. Spring flow tracings for Monument, Salt, and Horn Creeks are shifted one month to the left



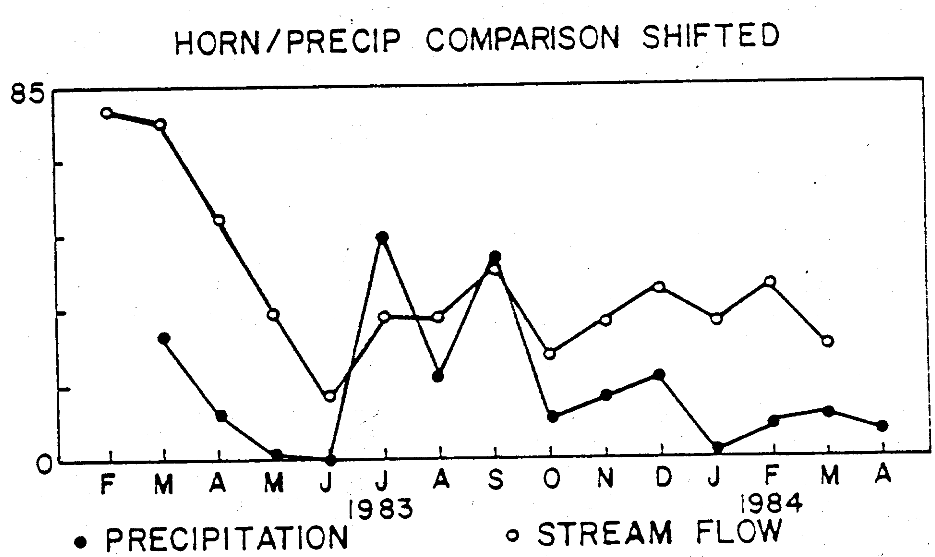


Figure 7.-Continued.

to flow at the springs is apparently less than one month for Hermit Creek and greater than one month but less than two months for the other three springs.

Table 6 shows the correlation coefficients calculated for flow at each of the springs and precipitation at the rim. Calculations were made for lags of less than one month, less than two months, and less than three months. The results of these calculations confirm the estimated lag times for each spring. The low correlation coefficients are due to the fact that the lags can only be narrowed to within a month's time with the data available. Consequently, an exact correlation coefficient of 1.0 would be highly probable. Also, the fact that much of the precipitation falling on the rim is lost to evaporation and evapotranspiration causes the correlation to be reduced. Correlations between infiltrating water and spring flow would be much greater.

Table 6. Precipitation/Spring Flow Correlations

	Hermit	Monument	Salt	Horn
0-1 month lag	0.39	-0.22	-0.17	-0.22
1-2 month lag	0.17	0.23	0.18	0.38
2-3 month lag	-0.02	-0.10	-0.01	0.08

The rapid reaction to changes in precipitation is quite different from the ground water systems on the north rim. Huntoon (1974a) states that the lag time for Bright Angel Creek, on the north side of the river, is three months. Further, he states that the summer increase in precipitation does not show up as increased flow in the creek. The winter lag is due to the storage of water as ice and snow on the north rim, and the decreased summer flow can be explained by increased evaporation and evapotranspiration. The increased evaporation during the summer also occurs on the south rim. The winter lag is much reduced if not completely eliminated on the Coconino Plateau. This is probably the result of the lower elevation along this rim. Snowfalls commonly melt and do not form deep packs.

Although Figure 7 shows a close relationship between the flow at each of the creeks and the precipitation, and also to each other, there are subtle differences which may be important in the understanding of the flow systems. Figure 7 shows a large peak in the precipitation for the month of September. The corresponding spring flow rate is different for each of the four creeks. Flow is reduced at Hermit Creek from the previous month, slightly increased at Monument, considerably increased at Salt, and somewhat increased at Horn Creek. The differing response to the input can be explained by the fact that the precipitation was a high intensity, short duration, summer thundershower with limited lateral extent. This storm occurred on September 10, 1984 (U. S. Dept. of Commerce, issued monthly) and may have dropped most of its precipitation in the area of the Bright Angel Fault, with little falling onto the Hermit basin. This caused those fractures and joints nearer the focus of the precipitation to be filled with water. The water was released at the springs, producing the peaks in the hydrographs.

The varied responses of the four springs to this single precipitation event may indicate that the flow at each of the creeks is composed of waters from both Hermit and Bright Angel basins. Those springs nearer to either basin are influenced to a greater degree by the waters of that system. Since both of the major ground water systems are fed by precipitation on the south rim, the flow from each basin would be very similar in discharge trends, except for those times when only one of the systems is pulsed by precipitation over its basin, such as may be the case in the example illustrated above.

If, however, precipitation was equally distributed over both the Hermit basin and the Bright Angel basin during the September 10 storm, it would be expected that an increase in flow would have occurred at each of the springs in the area. Flow measurements were made one week after the storm and again one month later. No such increase was observed at Hermit Creek. Although flash flooding in the karst springs of the north rim is documented (Huntoon, 1974a), it is unlikely that the fractures and faults within the area of study provide such an open conduit to the springs as to make flooding on the order of a few days lag (from rim to orifice) possible. Further, the flash floods of the karst systems are followed by a gentle recession lasting several weeks (Huntoon, 1974a). This would also be expected following the flow of such a flood in the Hermit basin. However, no such recession was observed. Also, the smaller basin areas of Horn and Salt Creeks would provide less storage capacity for such an extended post-flood recession than would Hermit basin. The storm of September 10 and the related hydrologic responses at each of the springs seem to indicate that there may be a direct hydraulic connection between the four studied springs.

The lag times for each creek may also be indicators of the length of the flow path. Although the range to which the period can be narrowed with the available information is quite wide, it does give us some information. We know that Hermit has a lag of less than one month and the others have lags of one to two months. This may indicate that the waters feeding Monument, Salt, and Horn Creeks travel a longer flow path, from Hermit and Bright Angel basins and, hence, have a longer lag time. This seems quite likely when one takes into account the fact that Monument, Salt, and Horn Creeks all have smaller basins that does Hermit and would require even less travel time to the orifices, than does the Hermit system, unless the water originated outside the apparent surface basins.

Another indicator of flow path length is the water chemistry. Table 4 and Figure 8 show that Salt Creek has the greatest concentration of dissolved material and Monument Creek is the next highest. In general terms, water chemistry can be tied to flow path length, i.e., the greater the flow length, the greater the amount of dissolved material. The waters of Salt Creek have the longest journey from infiltration to discharge. This is what would be expected if the source of the water is either Hermit basin or Bright Angel basin, or both. The next longest distance indicated by water chemistry is Monument Creek. The map distance is longer to Monument than to Horn from either of their adjacent large canyons. Also, an important factor is that the orifice of Monument Spring is in the Tapeats Sandstone, whereas, the orifice of Horn Creek is above the Tapeats. This indicates deeper flow and, hence, increased opportunity for solution of surrounding rock. Finally, Hermit Creek contains the least amount of dissolved solids as would be expected due to its direct flow system and shorter lag time.

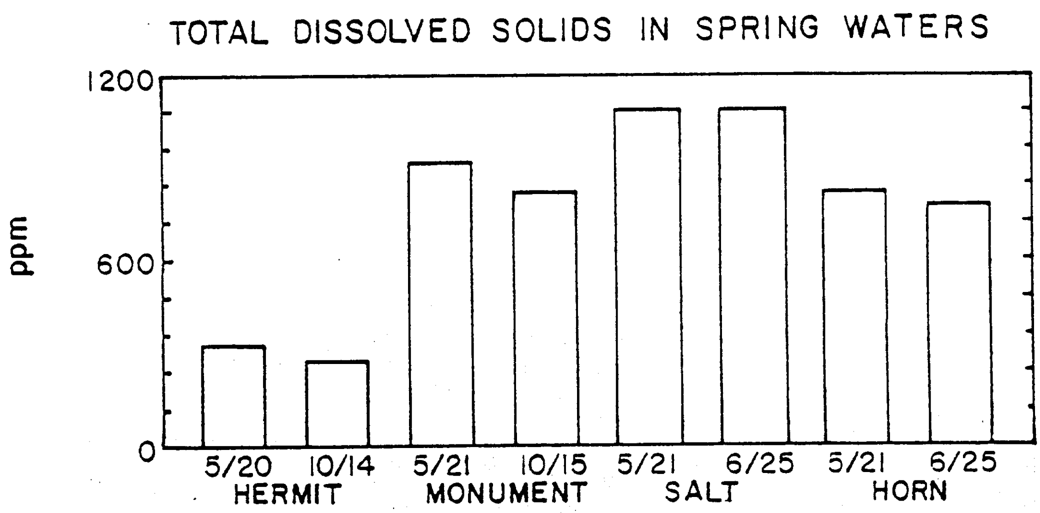


Figure 8.-TDS in spring waters during study (1983).

Figure 9 illustrates the water chemistry of the four springs in the form of Stiff diagrams. Each of the spring waters has a significantly different chemical character from the other three. Hermit Creek's water is of magnesium, calcium, bicarbonate nature. Monument Creek has magnesium, sodium, calcium, sulfate, chloride, bicarbonate water. Salt Creek has magnesium, calcium, sulfate water and Horn Creek's is magnesium, calcium, sulfate, bicarbonate in character. These classifications are based upon the percentage of equivalents per million of anions and cations as specified by Davis and De Wiest (1966).

Although the different water chemistry seems to

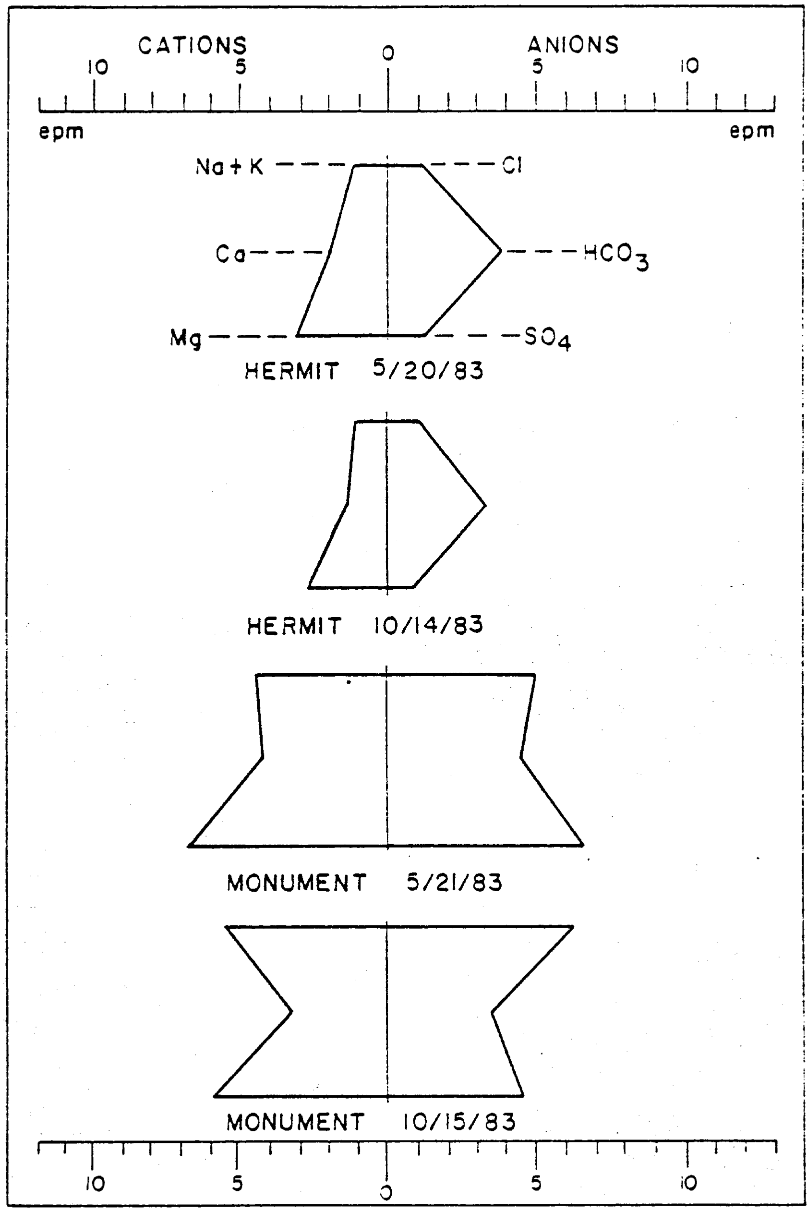


Figure 9.-Stiff diagrams of spring water chemistry.

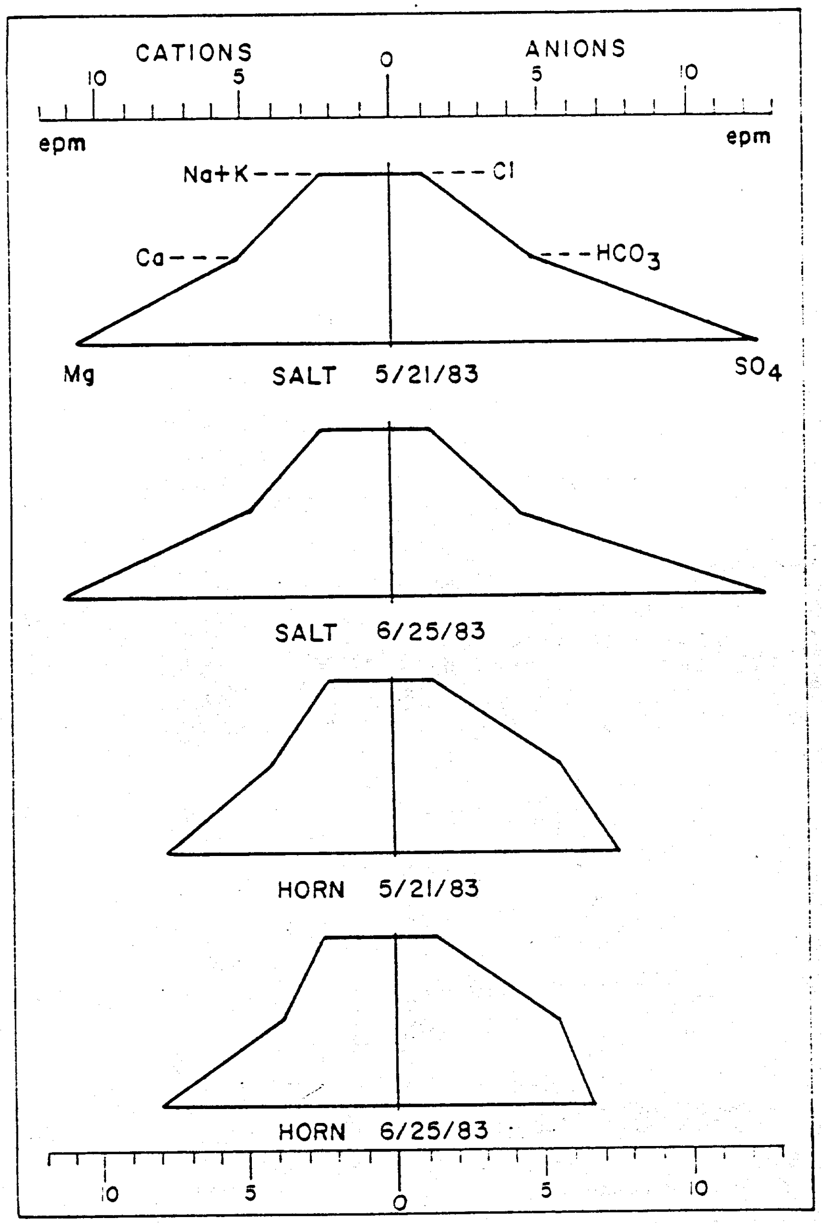


Figure 9.-Continued.

indicate waters of separate origins and flow systems, it is quite possible that local halite deposits in the strata immediately surrounding Monument Creek have a significant effect on the chemistry of this spring. The source of this halite is unknown in the stratigraphy of the area but it is likely that the local source is associated with the seep and the stalactites described earlier. Additional halite deposits may be present in the lower sections of the Tapeats Sandstone but may not have been exposed as yet because none of the other springs in the area of study flow from as low a stratigraphic position as does Monument's. The low stratigraphic positions of the other springs also seem to be the controlling factor in their chemistry. Hermit Creek issues mainly from the Muav Limestone and its waters may not encounter the sulfates which affect the other springs' chemistry, all of which have high concentrations of sulfate. Salt Creek seems to exhibit an anomalously low level of bicarbonate. There is a normal level of this ion in the water but it is masked upon first inspection by the high level of sulfate in the water.

Hermit Creek is the only drainage studied with any significant amount of surface drainage area on the rim. As stated earlier, Hermit's surface drainage encompasses 10 square miles above its lowest spring, of which approximately 7 square miles is on the rim. Monument, Salt, and Horn Creeks surface drainage basins are confined to the area below the south rim. Roughly, the surface areas above the spring orifices measure 2.5 square miles at Monument Creek and 1 square mile each at Salt and Horn Creeks.

When the size of the ground water basins (discussed earlier and shown in Table 7) are compared to the area of surface drainage there is an apparent difference. Both Hermit and Monument Creek have much smaller surface drainages than is indicated by the amount of flow from their springs. Salt and Horn Creeks, conversely, have much larger surface drainages than ground water basins. Table 7 also shows the approximate percentage of the precipitation that enters the ground water system and flows out at the springs. This percentage is based on the estimated total precipitation falling on the Tonto Platform during the study or 60 percent (15 inches) of the precipitation at the rim (25 inches). The figure 60 percent was derived from the ratio of the average precipitation at Phantom Ranch, in the inner gorge, over the average precipitation on the rim.

The differences shown in Table 7 seem to group the four springs into two separate categories or systems. Hermit and Monument Creeks can be grouped together on the basis of their surface/ground water drainage basin ratios and percentages of precipitation becoming spring flow. Salt and Horn Creeks are grouped due to their larger surface/ground water basin ratios and small percentage of precipitation flow-through.

Table 7. Drainage Basin Size and Flow Percentage

	Hermit	Monument	Salt	Horn
Surface drainage[1] (square miles)	10	2.5	1	1
Grnd. water drainage[2] (square miles)	34	5	0.1	0.2
Surface/Grnd. water drainage ratio	0.3	0.5	10	5
Total flow during study (cu. ft.)	$3.1x10^7$	$7.6x10^6$	$1.7x10^5$	$4.3x10^5$
Total precip.[3] during study (cu. ft.)	$3.8x10^8$	$8.7x10^7$	$3.5x10^7$	$3.5x10^7$
Approx. % of precip. becoming flow at springs	8.2	8.7	0.5	1.2

1 Drainage to lowest contributing spring.
2 Based on regional flow per unit area (0.021 cfs/mi^2).
3 Precipitation at Tonto level (1983-84).

These differences are thought to be a function of the amount of fracturing within the rock surrounding the creeks. If fracturing is extensive, such as at Hermit and Monument Creeks, the ground water basin area is extended by these fractures and the result is an increase in permeability within this basin. This increase in permeability may be responsible for the greater percentage of precipitation that is converted to spring flow. Salt and Horn Creeks, which have less fracturing and smaller ground water basins, show small percentages of precipitation converted to spring flow.

The migration of ground water in this area seems to occur by means of two main systems. The first, or rapid, system involves the collection of infiltrating precipitation into faults, joints, fractures, and solution structures. The collected water is then transported through the complex network of fractures and related structures to the orifice. The second, or slow, system is the storage and base flow component. This involves the filling of pore spaces and microscopic fractures with water during periods of high flow through the rapid system. This water is then slowly released during low flow periods as the head within the fractures is reduced. The storage is believed to exist mainly as relatively small, perched water tables above the more impervious strata. These small bodies of water are probably clustered around the fractures, faults, joints, etc., which fill the storage areas and in turn drain them again later.

It appears that the creeks are connected through a system of fractures. Waters from the two largest nearby ground water basins (Hermit and Bright Angel) contribute to the flow of these springs. It appears that these smaller creeks are incorporated into the drainage area of the main systems as outflow points for the waters trapped in those basins. Although very similar in their flow patterns, these individual springs exhibit separate flow characteristics. This division is based upon the amount of fracturing within the basin and the connection to the main systems of Hermit and Bright Angel basins. It is probable that the connection to the smaller springs as Salt and Horn Creeks is intermittant in nature. Water may only be forced into these smaller drainages during periods of high flow at Hermit and/or Garden Creeks. This results in these two springs going dry during extended periods of little precipitation. The connection to Monument Creek from Hermit is well developed and the flow at Monument Creek is, therefore, as permanent as is Hermit Creek.

Fractures are very important to the flow of ground water to all four studied springs. All of the springs except for those at Hermit Creek are fed by waters that have penetrated the Bright Angel Shale via extensive fracturing. Although large faults are not apparent at Salt Creek, sufficient fractures and joints are thought to be present to allow the passage of ground water.

The existence of the very widely extended zones of fracturing around faults can be seen in the patterns of erosion in the canyon. Also, and more importantly, the calculation of the ground water basin area at Hermit Creek further indicates the very large area around Hermit Fault which is fractured and acts as a hydrologic collecting structure to funnel water into the Hermit system. Generally, the larger faults have a greater fractured area surrounding them. This creates a larger collector structure, and greater flow from the associated spring. Nearly all the springs below the south rim are thought to be associated with some type of collector structure. The Bright Angel Fault is very large and controls the movement of ground water in a large area surrounding it (Metzger, 1961). It is also considered the collecting structure for the large springs at Indian Garden, east of Horn Creek. These large fractured areas extend well beyond the limits of the surface drainage basins, thereby collecting a greater amount of water than is available from the precipitation onto the surface basin alone.

CONCLUSIONS

The hydrographs generated from the data collected over the period of study indicate a close correlation between spring flow at the various creeks and the precipitation on the south rim. These graphs also show a lag time from recharge to discharge of less than one month at Hermit Creek and one month to two months at Monument, Salt, and Horn Creeks. This lag time is the general time of response of the discharge to a pulse of precipitation. This, however, does not allow accurate predictions of the level of flow at the springs because the actual residence time of any particular molecule of water within the system is unknown. The general understanding of the relative flow period allows a better understanding of the system and, hence, an ability to predict in general terms the approximate level of flow at each of the springs studied.

The length of the flow path for each of the springs is indicated by their relative lag times and water chemistry. These suggest a dual source within the area of study.

The structure of the area plays an integral part in the collection, movement, and flow of the spring water. The major structures are the Bright Angel Fault and the Hermit Fault and their associated areas of fracture.

The surface/ground water drainage basin ratio of each creek seems to be related to the amount of fracturing within the rock surrounding the basins. The two major faults act to expand the ground water basins of their ground water systems and then permit the flow of water through the impermeable strata within the Paleozoic section. These two faults are the sources of a portion of the water flowing at each of the creeks, in varying amounts.

The varied methods of investigation presented in this paper support a structurally-based, interconnected flow system within the area of study. This connection appears to be based mainly on the hydrologic effects of the Hermit and Bright Angel Faults which extend well beyond the limits of the apparent fractures into all of the area of study.

REFERENCES CITED

Colbert, E. H., 1974, The rocks and fossils of the Mesozoic, a brief statement, in Breed, W. J. and Roat, E. C. (eds.), Geology of the Grand Canyon: Flagstaff, Ariz., Mus. Northern Arizona and Grand Canyon Natural History Assoc., p. 77-80.

Davis, S. N., and De Wiest, R. J. M., 1966, Hydrogeology: New York, New York, John Wiley & Sons, 463 p.

Ford, T. D., and Breed, W. J., 1974, The younger Precambrian rocks of the Grand Canyon, in Breed, W. J. and Roat, E. C. (eds.), Geology of the Grand Canyon: Flagstaff, Ariz., Mus. Northern Arizona and Grand Canyon Natural History Assoc., p. 20-33.

Green, C. R., and Sellers, W. D., 1964, Arizona climate: Tucson, Ariz., Univ. of Arizona Press, 503 p.

Hamblin, W. K., and Murphy, J. R., 1969, Grand Canyon perspectives: a guide to the canyon scenery by means of interpretive panoramas: Brigham Young Univ., Geology Studies, Spec. Pub 1, 48 p.

Huntoon, P. W., 1974a, The karstic groundwater basins of the Kaibab Plateau, Arizona: Water Resources Research, v. 10, p. 579-590.

______, 1974b, The post-Paleozoic structural geology of the eastern Grand Canyon, Arizona, in Breed, W. J. and Roat, E. C. (eds.), Geology of the Grand Canyon: Flagstaff, Ariz., Mus. Northern Arizona and Grand Canyon Natural History Assoc., p. 82-115.

______, 1977, Relationship of tectonic structure to aquifer mechanics in the western Grand Canyon district, Arizona: Wyoming Water Resources Research Institute, series no. 66, 51 p.

Huntoon, P. W., Billingsley, G. H., Jr., Breed, W. J., Sears, J. W., Ford, T. D., Clark, N. D., Babcock, R. S., Brown, E. H., 1980, Geologic Map of the Grand Canyon National Park, Arizona: Grand Canyon

Natural History Assn., and Mus. Northern Arizona, Scale 1:62,500.

Johnson, P. W., and Sanderson, R. B., 1968, Spring Flow into the Colorado River - Lee's Ferry to Lake Mead: Arizona State Land Dept., Water Resources Rept. 34, 26 p.

La Rue, E. C., 1925, Water power and flood control of Colorado River below Green River, Utah: U.S. Geol. Survey Water-Supply Paper 556, 176 p.

McKee, E. D., 1974, Paleozoic rocks of Grand Canyon, in Breed, W. J. and Roat, E. C. (eds.), Geology of the Grand Canyon: Flagstaff, Ariz., Mus. Northern Arizona and Grand Canyon Natural History Assoc., p. 42-64.

Metzger, D. G., 1961, Geology in relation to availability of water along the South Rim, Grand Canyon, Grand Canyon National Park Arizona: U.S. Geol. Survey Water-Supply Paper 1475-C, p. 105-138.

Thybony, S., 1980, A guide to hiking the Inner Canyon: Grand Canyon, Ariz., Grand Canyon Natural History Assoc., 43 p.

U.S. Department of Commerce, issued monthly, Precipitation record at Grand Canyon National Park, in Hourly Precipitation Data, Arizona.

U.S. Geol. Survey, issued annually, Discharge record of the Colorado River, in Surface Water Supply of the United States, Part 9, Colorado River Basin.