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NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

ABSTRACT

The operation of multipurpose reservoirs in central Arizona requires timely and dependable streamflow and snowmelt information. Since 1965, conventional ground surveys and aerial observations have been used in an attempt to monitor rapidly changing moisture conditions in the Salt-Verde watershed. Since 1974, repetitive satellite snow-cover observations have greatly reduced the necessity for routine aerial snow-reconnaissance flights over the mountains. Frequent repetitive coverage is required to monitor rapid changes in snow cover. High-resolution (80-meter) multispectral imagery provided by the Landsat satellite series enabled rapid and accurate mapping of snow-cover distributions for small- to medium-sized subwatersheds; however, the imagery provided only one observation every 9 days of about a third of the watershed. Low-resolution (1-kilometer) imagery acquired by the ITOS and SMS/GOES meteorological satellite series provides the daily synoptic observation necessary to monitor the rapid changes in snow-covered area in the entire watershed. Short-term runoff volumes can be predicted from daily sequential satellite snow-cover observations. Hydrometeorological data relayed in near-real time by satellite and conventional telemetry and satellite snow-cover observations were used as an integral part of an early warning system during the floods of 1978 and 1979.

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INTRODUCTION

Difficulty in measuring and monitoring moisture conditions in large remote areas and the lack of timely information on rapidly changing moisture conditions cause serious water-management problems in Arizona and other semiarid regions. In central Arizona these problems have resulted in millions of dollars in property damage and in loss of life. Since 1974, the U.S. Geological Survey and the Salt River Project in cooperation with the National Aeronautics and Space Administration (NASA) have evaluated the repetitive aerial and satellite snow-cover observations and tested satellite data-collection systems for telemetry of hydrometeorological data from the Salt-Verde watershed.

Objectives of Study

The Arizona Test Site, which includes all the Salt-Verde watershed in central Arizona, is one of four test sites included in the NASA Applications Systems Verification Transfer (ASVT) on snow mapping. The principal objectives of the investigation in Arizona were to (1) evaluate the repetitive satellite imagery and aerial surveys for mapping snow-cover distributions, (2) develop techniques and procedures for systematic monitoring of snow cover and moisture conditions using remote-sensor methods, (3) test satellite data-collection systems to relay hydrometeorological data, and (4) perfect methods using satellite observations of snowpack to predict short-term and seasonal runoff derived from snowmelt.

Description of the Watershed

The Salt-Verde watershed includes about 34,000 km^2 in central Arizona. Nine subwatersheds were delineated for use in this study (Figure 1). A subwatershed is defined as the surface area that contributes runoff to a river either above a selected streamflow-gaging station or the surface area that contributes runoff between two selected stations on the main stem of a river. The altitude of the Salt-Verde watershed ranges from about 400 to 3,900 m above the National Geodetic Vertical Datum of 1929. The hypsometric curves in Figures 2 and 3 show the distribution of altitude in the Salt-Verde subwatersheds.

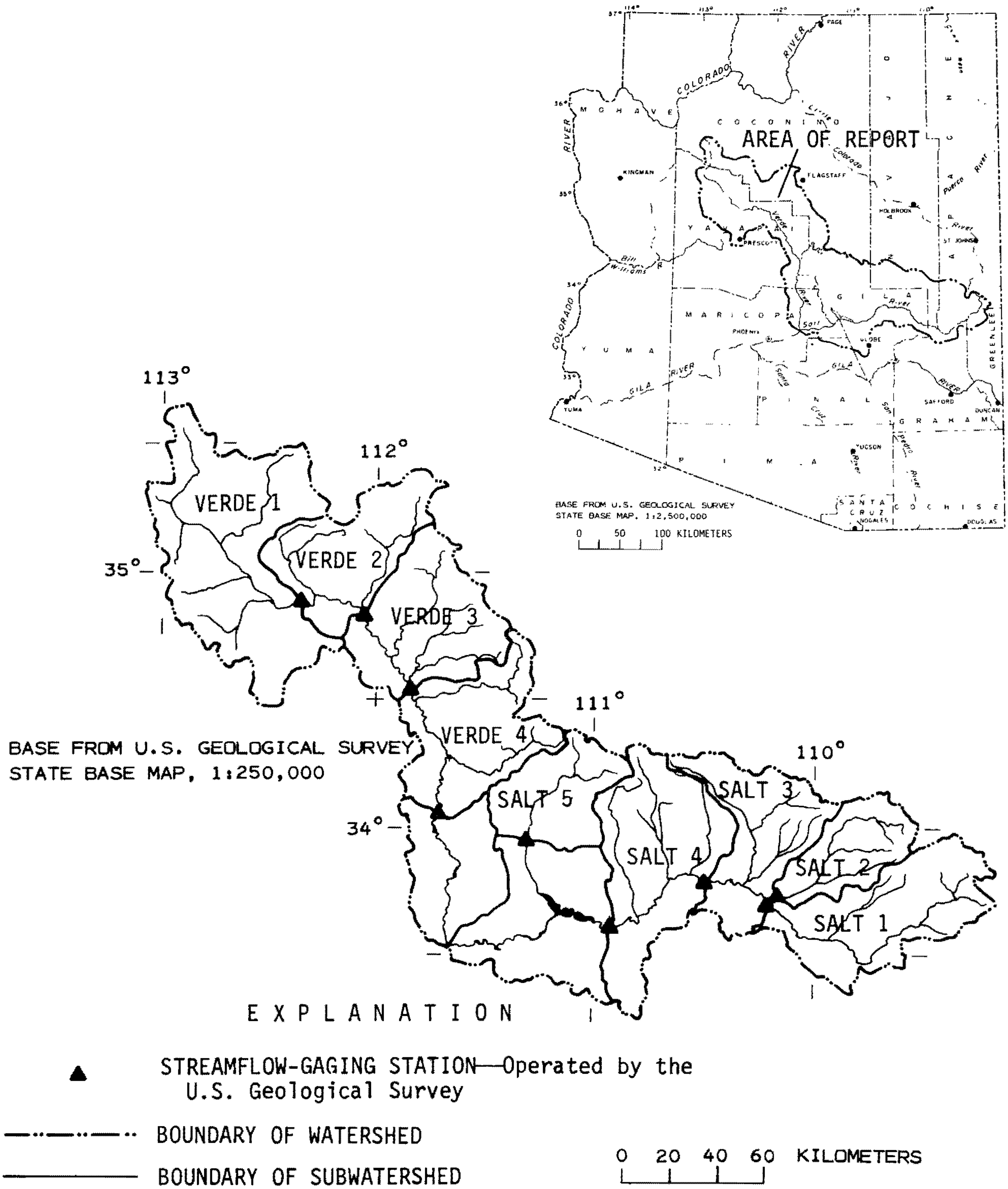


Figure 1. Area of report and subwatersheds.

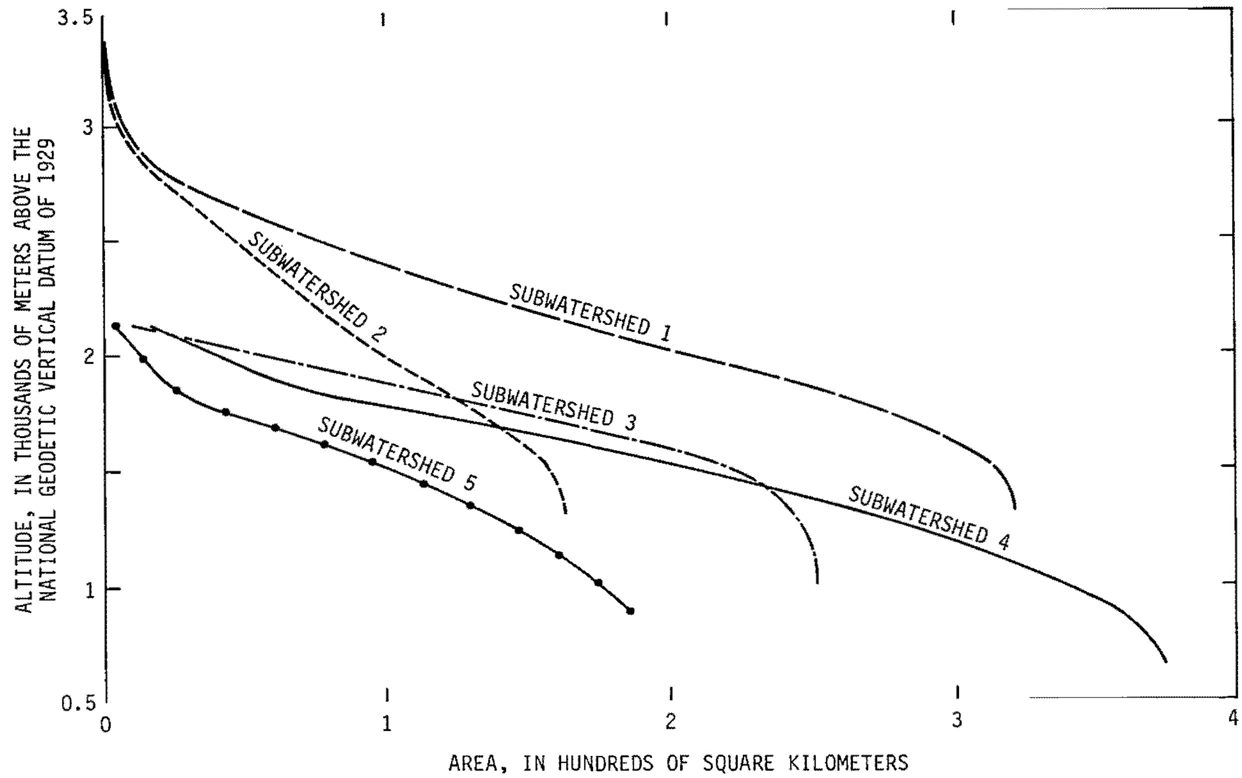


Figure 2. Distribution of altitude in the Salt River subwatersheds.

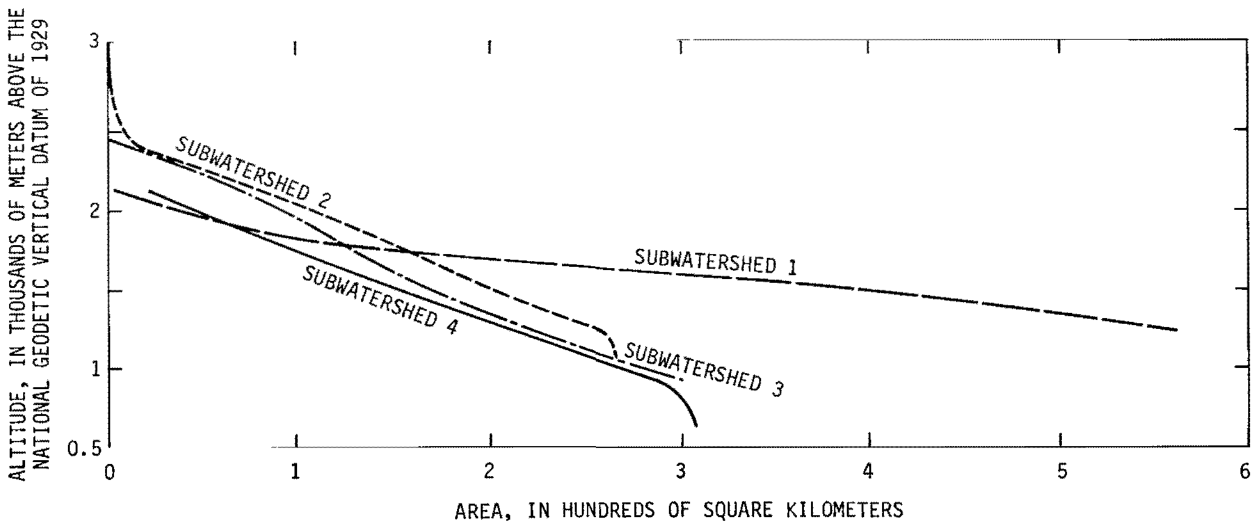


Figure 3. Distribution of altitude in the Verde River subwatersheds.

Precipitation and Runoff

The Salt-Verde watershed receives about 250 to 640 mm of precipitation annually, and about half the annual precipitation comes from winter storms (Reference 1). For 1913-74, winter storms produced about 75 percent of the average annual runoff (Reference 2). Much of the precipitation from these storms falls as snow.

In central Arizona the largest amount of runoff generally is along the north boundary of the Salt-Verde watershed. Runoff from the Salt and Verde Rivers is stored in a system of six reservoirs, which has a storage capacity of more than 2,500 hm^3. The reservoirs are operated by the Salt River Project to furnish water for municipal, industrial, and agricultural uses to more than 1 million people in the Salt River Valley near Phoenix. In addition, the reservoirs furnish hydroelectric power and limited flood protection to the Phoenix area. The combined annual flow of the Salt and Verde Rivers and the volume of water stored in the reservoir system during 1946-74 are shown in Figure 4. As shown in the figure, the annual runoff into the Salt and Verde Rivers above the Salt River Project reservoirs is highly variable.

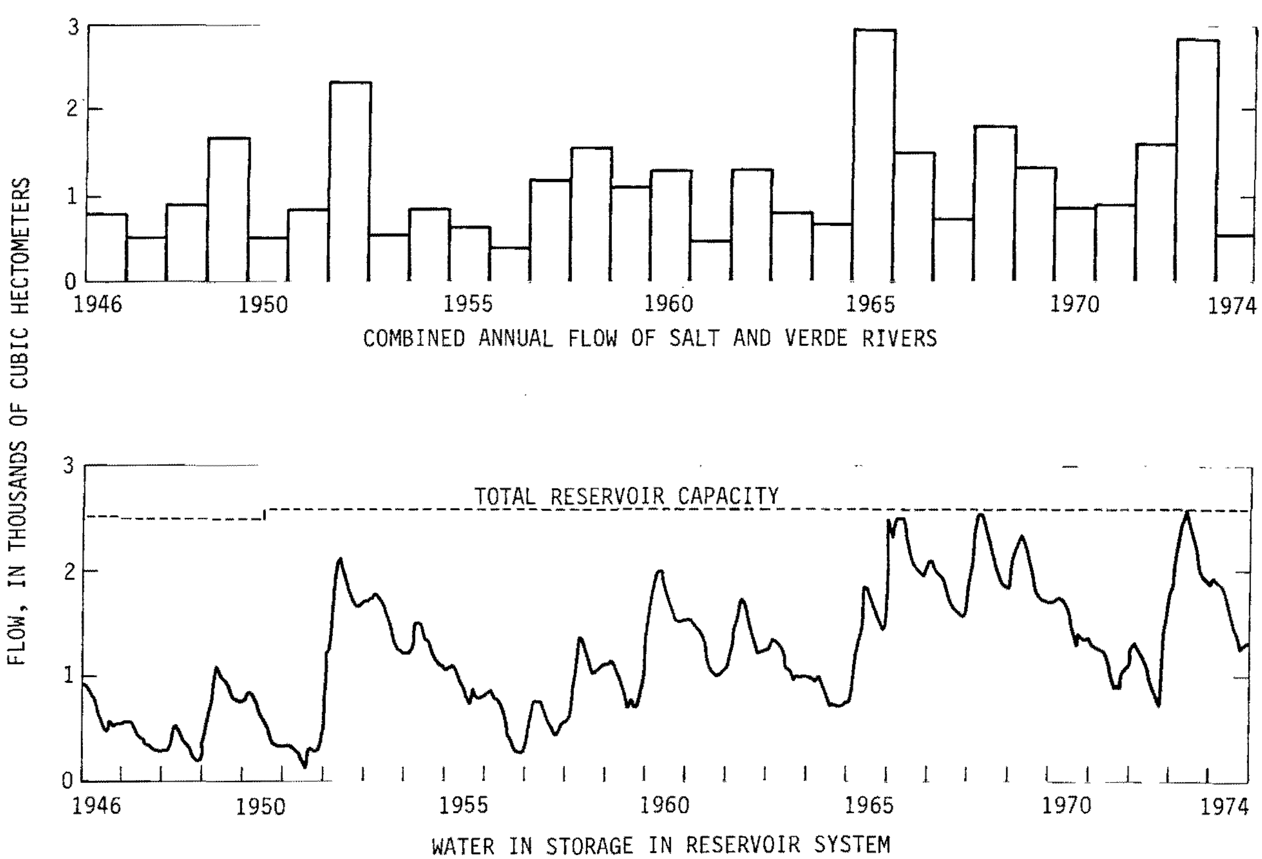


Figure 4. Combined annual flow of Salt and Verde Rivers and water in storage in the reservoir system, 1946-74.

Verde River subwatershed 1 occupies 39 percent of the Verde part of the watershed but yields only 5 percent of the average runoff to the reservoirs on the Verde River (Table 1). Verde River subwatersheds 2, 3, and 4 occupy

Table 1

Selected Winter Runoff Data for the Salt-Verde Subwatersheds

Subwatershed	Area, in square kilometers	Percentage of subtotal	Median altitude, in meters	Runoff, October 1972-May 1973			Runoff, October 1973-May 1974			Average October-May runoff, 1966-74		
				Cubic hectometers	Percentage of runoff	Cubic hectometers per square kilometer	Cubic hectometers	Percentage of runoff	Cubic hectometers per square kilometer	Cubic hectometers	Percentage of runoff	Cubic hectometers per square kilometer
Verde River part of the watershed:												
Subwatershed 1..	5,590	39	1,630	61.3	4	0.011	14.4	9	0.003	23.0	5	0.004
Subwatershed 2..	2,650	18	1,870	293	20	.111	34.2	21	.013	94.2	20	.036
Subwatershed 3..	3,000	21	1,600	546	37	.182	20.4	13	.007	[1]360	[1]75	[1].059
Subwatershed 4..	3,110	22	1,510	565	39	.182	90.4	57	.029			
Subtotal.........	14,350	100	-----	1,465.3	100	.102	159.4	100	.011	477.2	100	.033
Salt River part of the watershed:												
Subwatershed 1..	3,190	25	2,180	954	37	.299	53.3	24	.017	233	27	.073
Subwatershed 2..	1,640	13	2,130	365	14	.222	54.8	25	.033	135	16	.082
Subwatershed 3..	2,510	20	1,800	153	6	.061	41.4	19	.016	134	15	.053
Subwatershed 4..	3,740	28	1,580	663	26	.177	40.2	18	.011	236	27	.063
Subwatershed 5..	1,750	14	1,540	453	17	.259	29.4	14	.017	128	15	.073
Subtotal.........	12,830	100	-----	2,588	100	.20	219	100	.017	866	100	.067

[1]Combined runoff for subwatersheds 3 and 4.

61 percent of the Verde part of the watershed and yield about 95 percent of the runoff—the unit runoff is about proportional to drainage area. Salt River subwatersheds 1, 2, and 5 yield the greatest unit runoff in the Salt-Verde watershed.

Although the drainage areas above the reservoirs on the Salt and Verde Rivers are about equal in size, runoff from the Salt River part of the watershed generally is about two times the runoff from the Verde River part of the watershed. The storage capacity of reservoirs on the Verde River is only 392 hm^3 or about 16 percent of the capacity of the Salt-Verde reservoir system. The small storage capacity of the reservoirs on the Verde River necessitates the release of water into the normally dry channel of the Salt River above Phoenix during periods of unusually large runoff.

The volume of runoff in eight of the nine Salt-Verde subwatersheds was computed for 18-day intervals, which correspond to the periods between Landsat images during the November 1972 to June 1973 winter runoff period (Figures 5 and 6). (See section entitled "Landsat Systems and Imagery" for description of satellite imaging systems.) The data indicate that large differences in total and unit volumes of runoff occurred in the subwatersheds. The significance of these differences is discussed in the section entitled "Snow-Cover Depletion and Runoff."

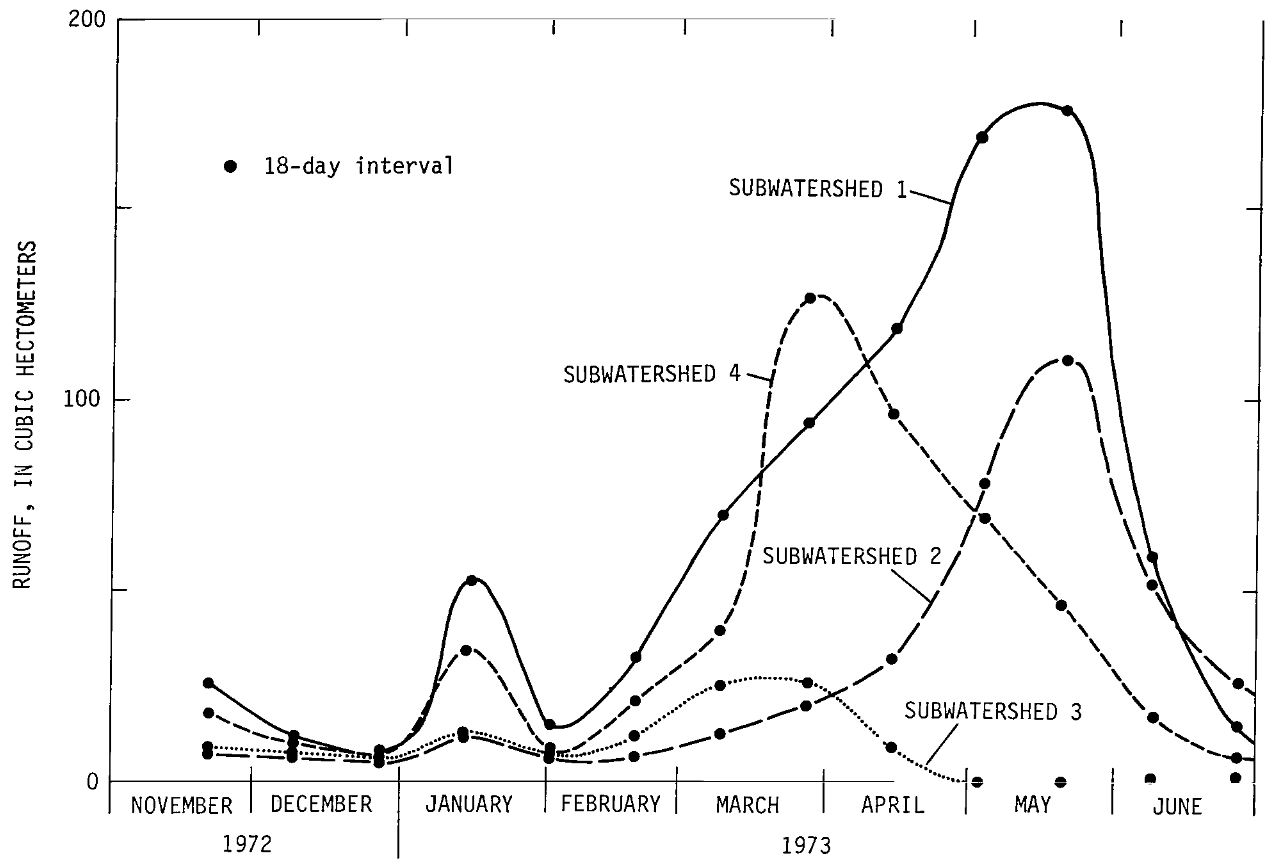


Figure 5. Winter runoff for 18-day intervals, Salt River subwatersheds.

AERIAL SNOW-COVER OBSERVATIONS

Distribution and Depth of Snow Cover

Information on the rapid changes in the distribution and depth of snowpack in the Salt-Verde watershed is needed for effective water-resources management. Most of the established snow courses, however, are at altitudes of more than 2,100 m above the National Geodetic Vertical Datum of 1929 in the seasonal snowpack zone. Low-level aerial reconnaissance flights were made to collect information on changes in the distribution, depth, and condition of the ephemeral snowpack below an altitude of 2,100 m. During 1965-68, the first snow maps were prepared at a scale of 1:3,000,000 from notes taken during each flight (Reference 3).

Aerial observations of snow depths and direct inflight mapping of snow-cover distributions on the Salt-Verde watershed were first attempted by Salt River Project personnel in 1969. The edge of the snowpack was mapped on a mylar overlay of an aeronautical chart at a scale of 1:1,000,000; the chart showed land-surface altitudes, the major drainage network, and the boundary of the

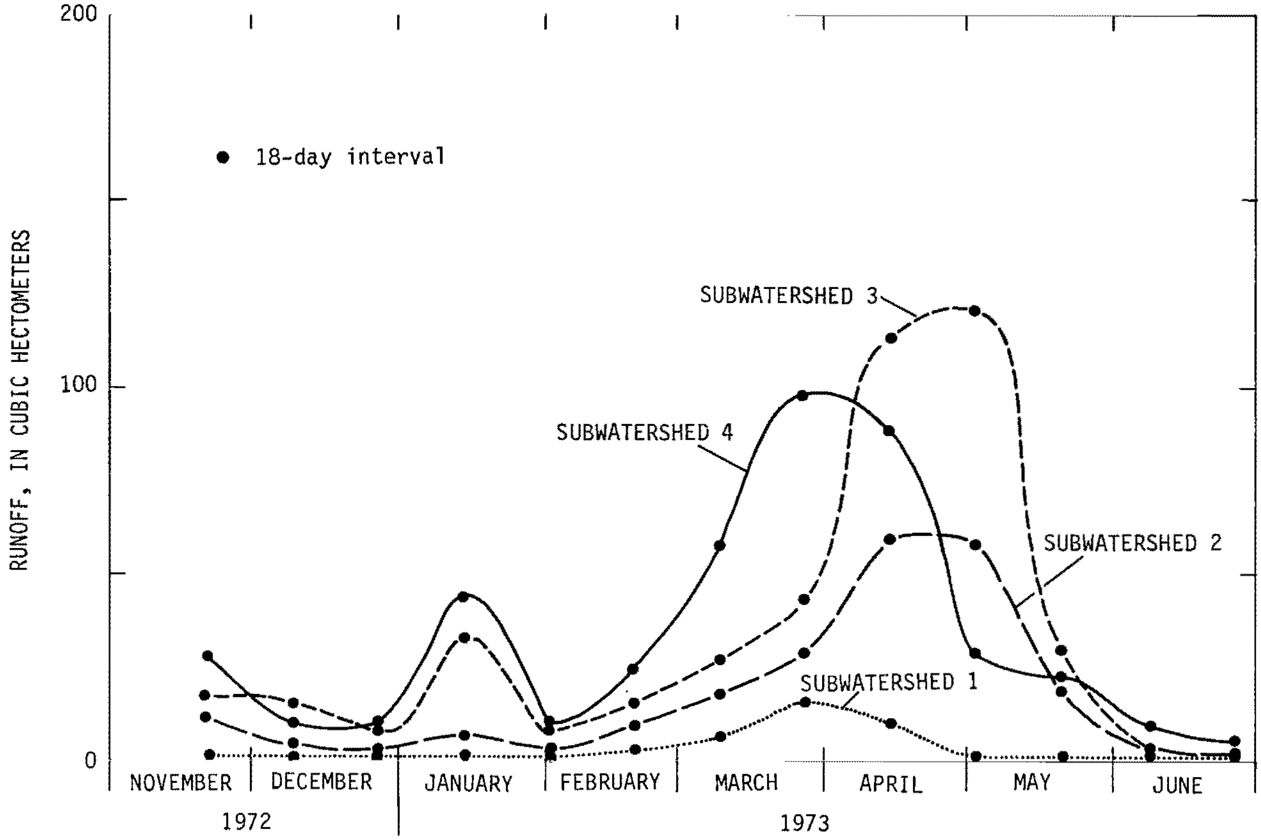


Figure 6. Winter runoff for 18-day intervals, Verde River subwatersheds.

watershed (Reference 3). In the spring of 1975, 4- to 6-hour aerial reconnaissance flights were made over all or parts of the Salt-Verde watershed to collect information on the distribution and depth of snow cover and to train additional aerial observers. Maps showing snow-cover distributions were prepared using visual mapping techniques and a Landsat image map at a scale of 1:1,000,000 (Reference 4). In 1976 and 1977 maps showing snow-cover distributions were prepared using visual mapping techniques and aeronautical charts at a scale of 1:500,000 (Figure 7).

Low-level aerial observations of snow markers and other features, such as logs and fences, are used by Salt River Project personnel to collect information on snow depths in the Salt-Verde watershed. In the mountains in central Arizona strong surface winds often prevent the low-level aerial observations necessary to make accurate estimates of snow depths; therefore, during the winter of 1974-75, an attempt was made to obtain oblique aerial photographs of the snow markers in the upper Salt-Verde watershed. A technique was developed to obtain economical high-resolution photographs of the snow markers at a safe altitude—150 m above land surface (Reference 4). The combination of a motorized 35-mm camera fitted with a 400-mm focal-length

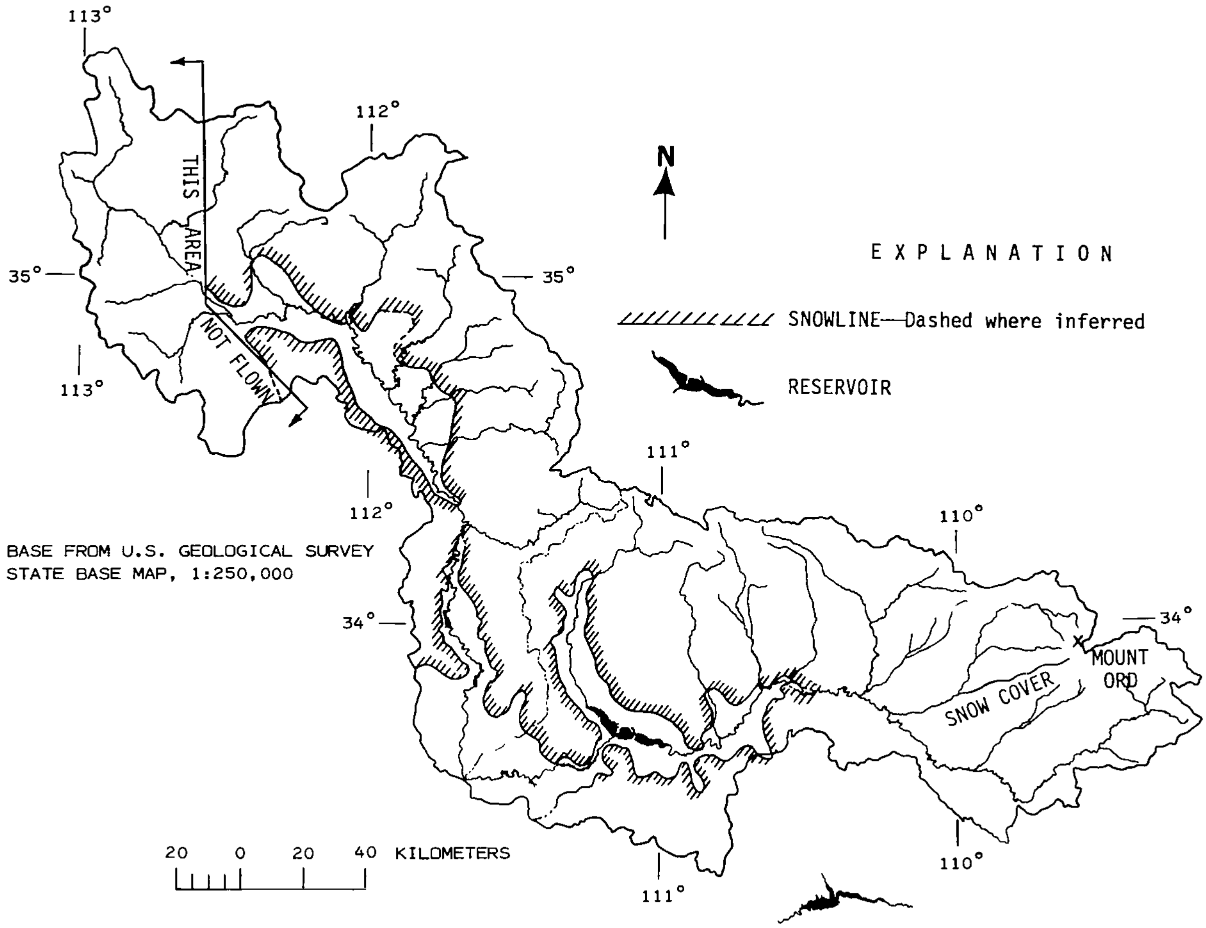


Figure 7. Distribution of snow cover as determined by visual aerial mapping techniques, Salt-Verde watershed, March 8, 1976.

lens and high-speed color film provided the required scale and quality of photographs (Figure 8). The motorized camera furnished multiple images of snow markers in a single pass of the aircraft, and the high-speed color film facilitated estimates of snow depths at snow markers photographed under cloudy or overcast conditions. Because the dimensions—height, width of bars, and spacing between adjacent bars—of the snow markers were known, it was possible to determine snow depth at an estimated accuracy of ±75 mm from photographs taken at as much as 300 m above the terrain. The shadow of the snow marker generally is seen more easily than the vertical marker itself and can be observed with the least distortion when photographed directly toward the sun (Figure 8).

Advantages and Limitations

Aerial observations of snow-cover distribution provide valuable information during periods of cloud cover that preclude satellite snow-cover observations. Aerial observations also allow rapid collection of information on snow depth and runoff conditions; however, these observations require

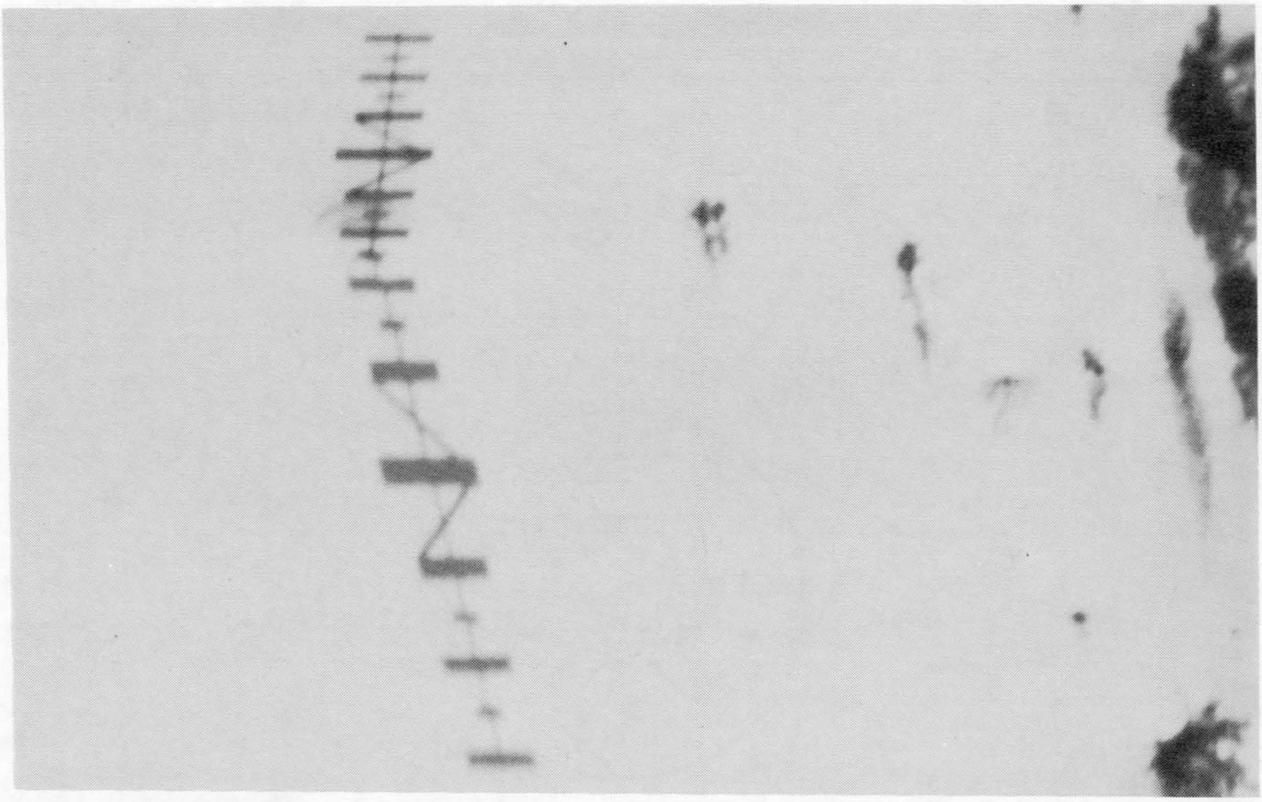


Figure 8. Snow marker on Mount Ord. Oblique aerial photograph taken at 150 m above the terrain.

experienced observers, many hours of hazardous flying over mountainous terrain, and considerable expense. Snow-cover distributions mapped by inexperienced observers tend to be highly generalized. A major advantage of using oblique aerial photographs of snow markers to determine snow depth is that standard photographic and projection equipment can be used. Another advantage of the technique is that it provides low-cost permanent records of snow depths. The photographs can be evaluated in the office as opposed to an observer attempting to read the snow markers from low-flying aircraft.

SATELLITE SNOW-COVER OBSERVATIONS

Photographs taken in March 1969 by the Apollo-9 astronauts, using hand-held 70-mm cameras, provided a detailed synoptic view that could be used to map snow-cover distributions in the Salt-Verde watershed. Although the Apollo-9 photographs indicated that satellite imagery could provide a rapid measure of snow-cover distribution, aerial observations indicated that frequent repetitive coverage was required to monitor the rapid changes in snow cover in the Salt-Verde watershed. Data from Landsat, Improved TIROS Observational Satellite (ITOS), and Synchronous Meteorological Satellite/Geostationary Operational Environmental Satellite (SMS/GOES) systems were evaluated to provide timely information on snow cover and moisture conditions in the Salt-Verde watershed (Figure 9).

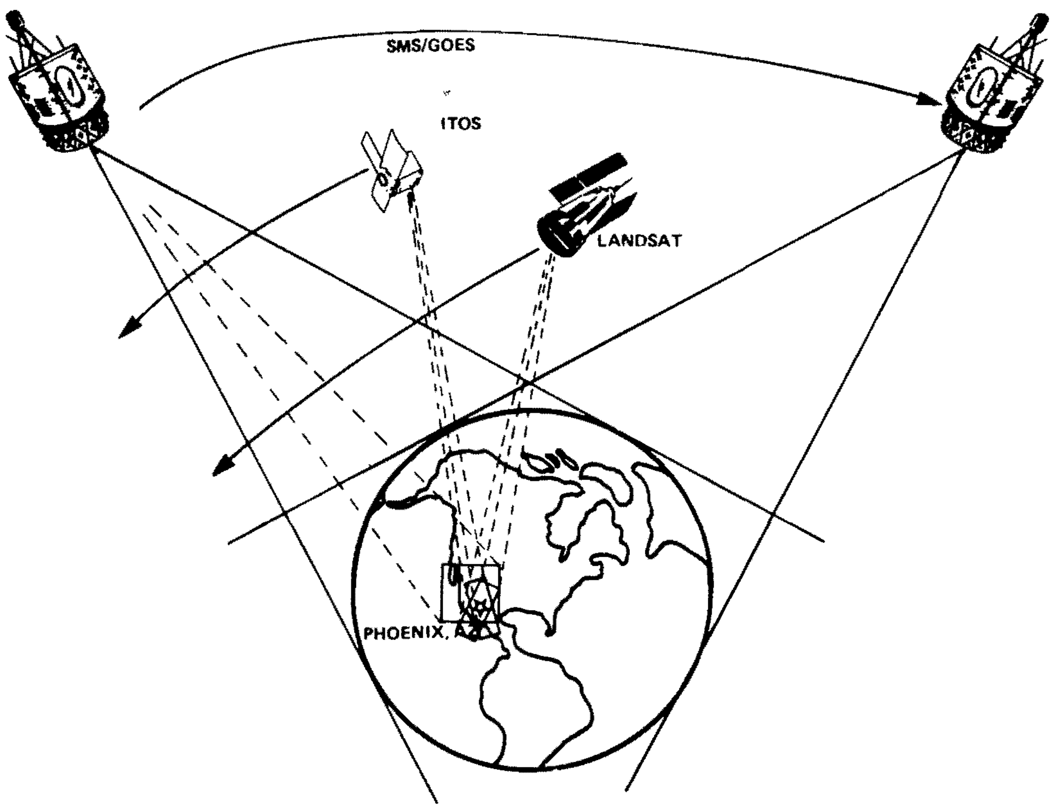


Figure 9. Satellite imaging systems.

Landsat Systems and Imagery

The experimental Landsat satellite series consists of satellites that operate in nearly circular, sun-synchronous, polar orbits at altitudes of about 925 km. Multispectral scanners (MSS) aboard the satellites provide high-resolution imagery (80-m ground resolution) in four spectral bands that range from the visible to the near-infrared parts (0.5 to 1.1 μm) of the spectrum (Reference 5). Landsat images cover 185- by 185-km areas, and two Landsat satellites provide coverage of any ground point once every 9 days. The Landsat data-collection system (DCS) was successfully tested to relay hydro-meteorological data from selected streamflow-gaging stations and snow-monitoring sites.

The MSS imagery is virtually orthographic and provides sufficient resolution for mapping snow-cover distributions at scales of 1:1,000,000 and 1:500,000 using conventional photointerpretation techniques. Snow-covered areas are most easily delineated on MSS band 5 (0.6 to 0.7 μm) images. MSS band 7 (0.8 to 1.1 μm) images also are useful in snow-cover mapping, because these wavelengths penetrate thin cloud layers and haze.

Visual Interpretation

Visual interpretation of 1:1,000,000 Landsat MSS band 5 (0.6 to 0.7 μm) imagery enables rapid and direct mapping of snow-cover distributions using conventional photointerpretation techniques. The snowline is traced onto a transparent overlay that includes the watershed outline and major drainages, and the areal extent of the snow cover is determined using a manual planimeter or a suitable grid. Although this technique allows inexpensive measurement of snow-cover distributions, the degree of precision is dependent on the skill and experience of the interpreter. An experienced interpreter can map snow-cover distributions in the 34,000-km^2 Salt-Verde watershed in less than 2 hours from the Landsat imagery; in contrast, about 5 hours of flight time and 1 to 2 hours of map preparation are required to map the same area using aerial reconnaissance techniques. In the Salt-Verde watershed snow-cover distributions mapped by personnel of the Salt River Project by visual interpretations of Landsat imagery and aerial observations taken on or about the same dates during the winter of 1972-73 agreed within 2 percent (Reference 6). The average difference between the mapping techniques for seven dates was 7 percent.

Color-Additive Viewing

Color-additive viewing of the multispectral Landsat images—MSS bands 4, 5, and 7 color composites—enhances the contrast between snow-covered and snow-free areas and greatly facilitates snow-cover mapping in densely forested areas (Figure 10). Snow-cover measurements can be made from color-composite images using transparent-overlay techniques. The main disadvantages of using the color-additive viewing technique are the high cost of projection equipment and the time required to make the area measurements.

Electronic Image Enhancement

Use of the electronic density-slicing technique and appropriate watershed masks enables the rapid determination of the percentage of snow-covered area in small to intermediate watersheds. The density slicer makes a television scan of a masked transparency copy of the black and white satellite image, the enhanced image is displayed on a color television monitor, and the percentage of snow-covered area is measured by means of the electronic planimeter. The main disadvantages of the density-slicing technique are the high cost of equipment and the low precision of measurement in small areas. Examples of color-enhanced Landsat images are shown in Figure 11.

The Stanford Research Institute Electric Satellite Image Analysis Console (ESIAC) was used to determine snow-cover distributions in selected subwatersheds during the winter of 1974-75. ESIAC uses television scanning of film transparencies of satellite imagery and computer storage of the scanned imagery and watershed maps, which enables the use of animation methods (Reference 7). The system enables the rapid registration, storage, and retrieval of as much as several hundred frames of satellite imagery. Watershed maps can be superimposed on the imagery, and time-lapse sequences can be produced. Quantitative measurements of pixel (picture-element) radiance and

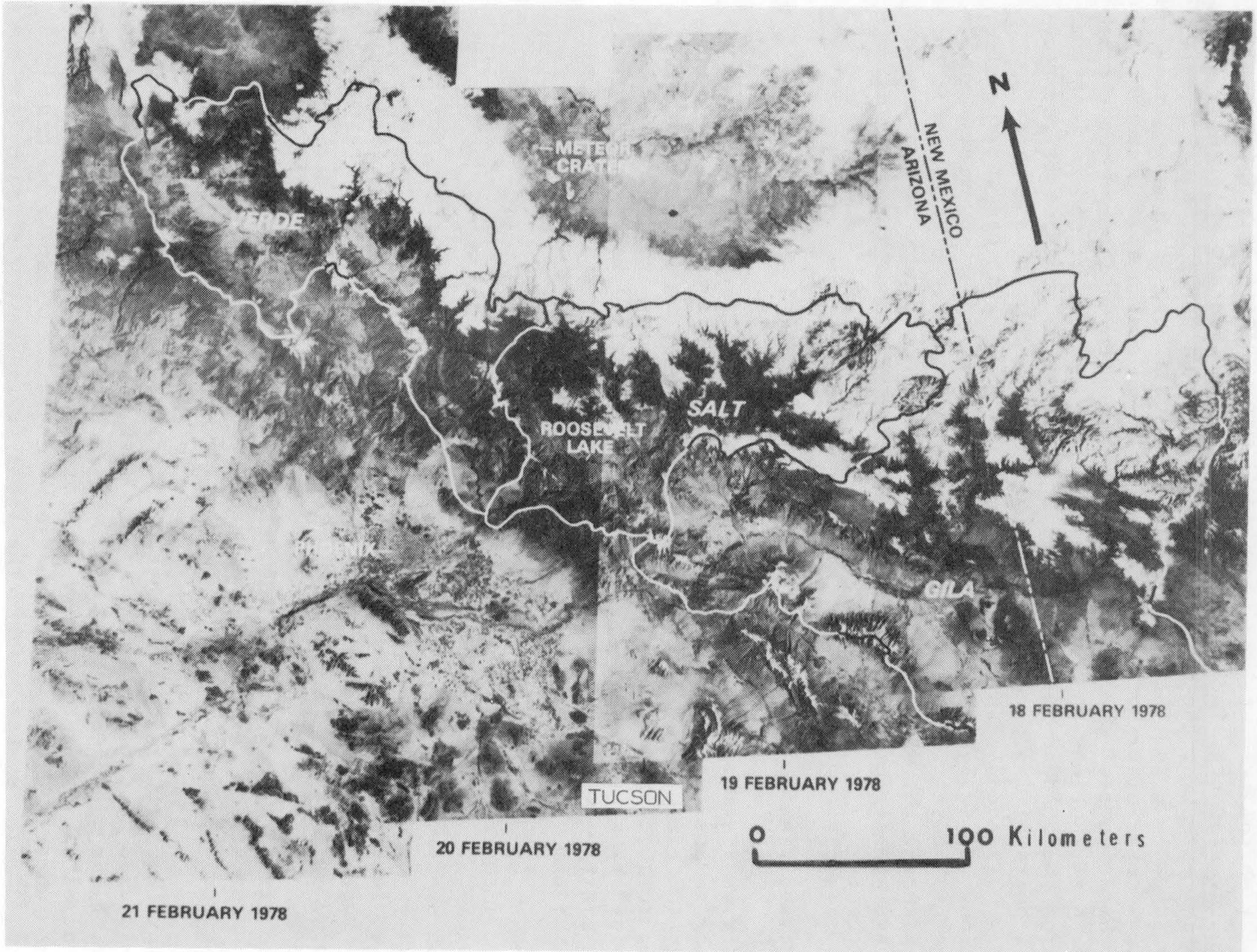
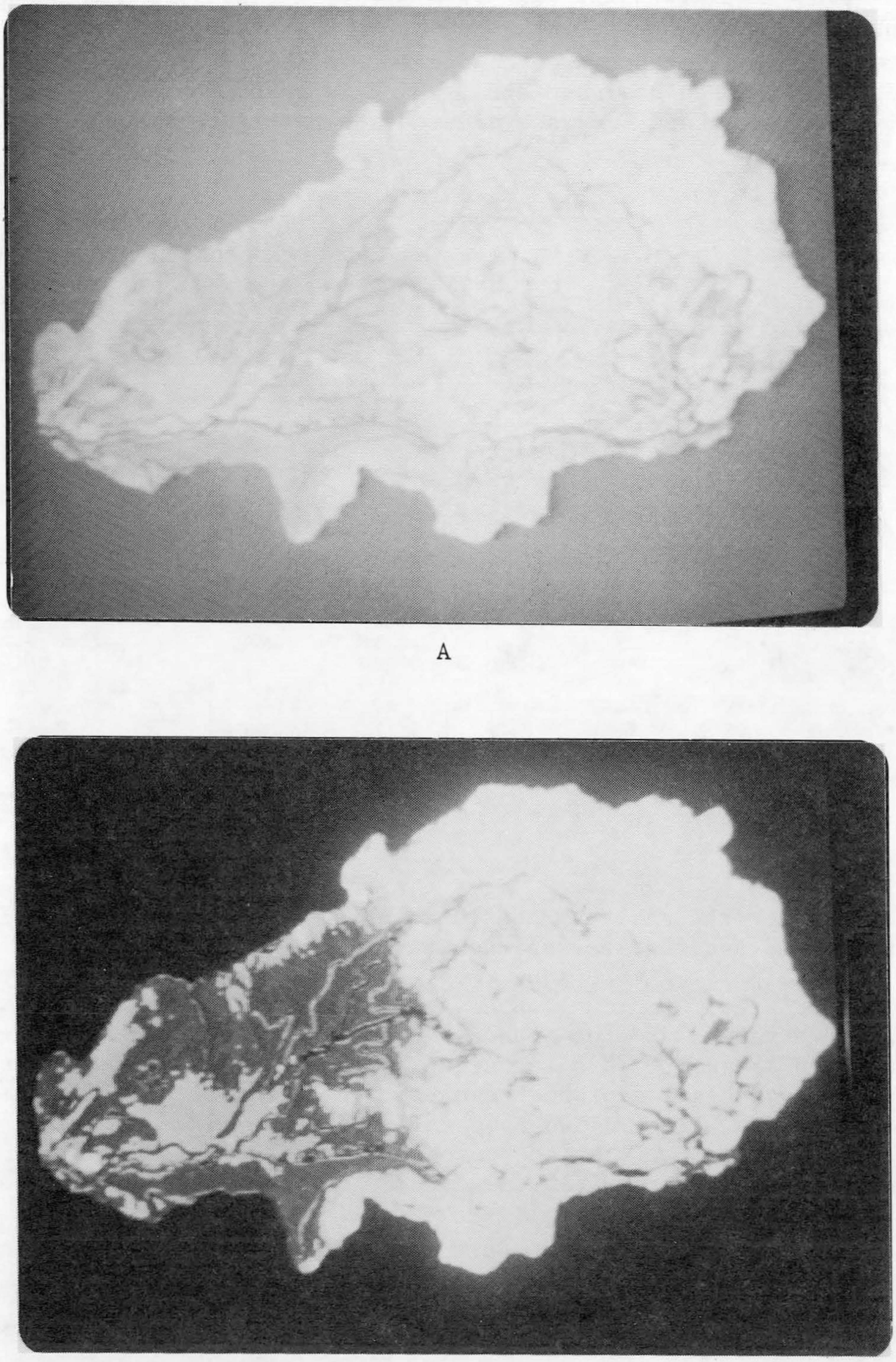


Figure 10. Landsat image mosaic of the Salt-Verde watershed.



A

B

Figure 11. Enhanced Landsat images (band 5) of Salt River subwaterhsed 2 using density-slicing techniques. A, Masked Landsat image showing lines of equal altitude and principal streams. B, Enhanced Landsat image; snow-covered areas are white.

pixel counts are provided for the rapid determination of snow-covered areas. Ten cloud-free Landsat images that include Verde River subwatersheds 3 and 4 and Salt River subwatershed 5 were selected for analysis using ESIAC; the small West Clear Creek drainage area, which is in the northeastern part of Verde River subwatershed 4, was evaluated separately (Table 2).

Table 2

Percentage of Snow Cover in Selected Subwatersheds as Determined by the ESIAC System

Date	Verde River subwatershed 3		Verde River subwatershed 4		West Clear Creek		Salt River subwatershed 5	
	Area, in square kilometers	Percentage of snow cover	Area, in square kilometers	Percentage of snow cover	Area, in square kilometers	Percentage of snow cover	Area, in square kilometers	Percentage of snow cover
1974								
December 17.....	153	5.1	43.5	1.4	36.6	5.9	0	0
1975								
January 4.......	1,022	34	953	31	556	89	290	17
February 1......	-----	-----	1,092	35	613	98	126	7.2
February 9......	828	28	399	13	369	59	121	6.9
February 18.....	1,543	51	1,463	47	617	99	1,269	73
February 27.....	904	30	509	16	476	76	99	5.7
March 17........	1,378	46	1,059	34	617	99	256	15
April 4.........	506	17	425	14	390	62	49	2.8
April 22........	159	5.3	35	1.1	27	4.3	1.8	.1
May 10..........	0	0	0	0	1.9	.3	0	0

The first phase of the analysis consisted of entering bands 5 and 7 Landsat images into ESIAC and registering the imagery to watershed maps. A single radiance-threshold level technique then was used to estimate the percentage of snow-covered areas using only Landsat MSS band 5 imagery. All pixels having radiance values greater than a threshold value chosen by the operator were classified as snow. This technique is the same as the density-slicing technique and produces acceptable results. The ESIAC also allows simultaneous threshold slicing in two spectral bands, and altitude contours can be superimposed electronically on the composite images. This technique produced consistent snow-cover determinations for the entire image and for the selected subwatersheds (Table 2).

Special-image masks showing the outline of each subwatershed, image date, and percentage of snow cover were prepared and superimposed on the enhanced imagery. The combination of sequential composite images was then copied on 35- and 16-mm color film from the ESIAC color-television display. A 35-mm color slide presentation and a 16-mm color movie film were prepared to show the time-lapse sequence of snow-cover changes.

Digital Computer Techniques

The Landsat MSS data are available in digital form on computer-compatible tapes (CCTs). Digital-pattern (spectral) recognition systems—such as the LARSYS Version 3 of Purdue University, STANSORT-2 of Stanford University, and General Electric Image-100 system—have been used to produce snow maps from digital Landsat data (Reference 8). The General Electric Image-100 system was used to evaluate Landsat CCTs for snow-cover mapping in the Salt-Verde watershed. The system provided high-precision mapping at slow to moderate speeds. The disadvantages of using the systems for snow mapping are the high cost of digital tapes and digital-image processing and the delay involved in acquiring the Landsat digital tapes.

Advantages and Limitations

The main advantage of using Landsat imagery for snow-cover mapping is that the imagery is nearly orthographic at a scale of 1:1,000,000, which enables direct visual interpretation of snow-covered areas. Using simple overlay techniques, snow-cover measurements can be obtained at low cost. Color composites of Landsat multispectral images increase the contrast between snow-covered and snow-free areas. The main limitation of using Landsat imagery for snow-cover mapping is that only one observation is available every 9 days for part of the Salt-Verde watershed. During periods of rapid snowmelt, thin snow cover can melt in less than 9 days. Six Landsat images taken on 3 consecutive days are required to cover the entire watershed (Figure 10). Cloud cover often prevents effective Landsat snow-cover observations for long periods of time. Another limitation is the time delay between acquisition of the imagery by the satellite and receipt of the imagery by users. The satellite imagery must be available in near-real time to be of use for the short-term predictions of snowmelt and runoff.

ITOS System and Imagery

During the first part of the study, the National Environmental Satellite Services (NESS) used imagery from the ITOS operational satellites (NOAA series) to produce areal snow-cover maps of selected river basins including the Salt-Verde watershed (Reference 9). The satellites operate in sun-synchronous polar orbits about 1,500 km above the Earth. Very High Resolution Radiometers (VHRRs) aboard the satellites provide daily coverage of the Western United States in the visible part of the spectrum (0.6 to 0.7 μm) and twice-daily coverage in the thermal infrared (10.5 to 12.5 μm) part of the spectrum (Reference 10). The VHRR imagery provides horizon-to-horizon coverage, has a resolution of about 1 km at the nadir—the point vertically below the spacecraft along a line perpendicular to the surface of the Earth—and has a scale of about 1:10,000,000 (Reference 10). The imagery provides a highly distorted panoramic view of the surface of the Earth that requires geometric correction before it can be related to planimetric maps (Figure 12).

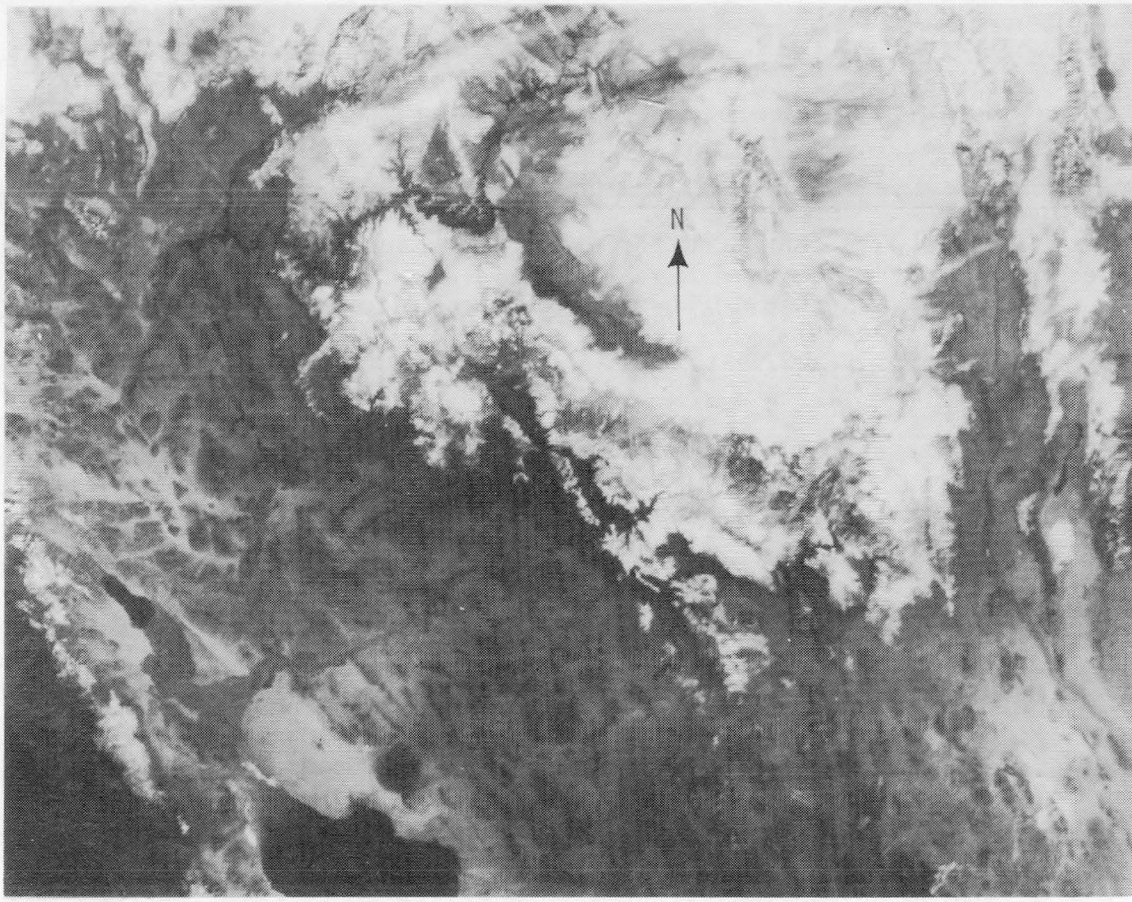


Figure 12. NOAA VHRR image taken in the visible part of the spectrum.

Methods of Analysis

A Zoom Transfer Scope (ZTS)* was used by NESS to enlarge and stretch the VHRR imagery and to project the corrected image on watershed maps at a scale of 1:2,500,000 (Reference 9). The snowline—as visually interpreted on the corrected image—was then traced on an overlay of the watershed map. The percentage of snow-covered area was then determined either by manual or by electronic-planimeter methods. Copies of the overlay and the percentages of snow-covered area were transmitted to the Salt River Project by telecopier within 24 hours of the satellite overpass.

Advantages and Limitations

The main advantages of using the NOAA VHRR imagery for snow-cover mapping are that the imagery is available on a daily basis and that the entire Salt-Verde

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*The use of the brand name in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

watershed is covered on a single image. The main limitations of using the imagery are its low resolution and variable geometric distortion. The distortion requires the use of moderately expensive equipment to perform the geometric corrections and scale changes necessary to relate the VHRR imagery to planimetric watershed maps.

SMS/GOES System and Imagery

The Synchronous Meteorological Satellites (SMS) now in geostationary orbit are prototypes for the satellite series Geostationary Operational Environmental Satellites (GOES). The system uses two satellites in geostationary orbit at about 35,000 km above the Earth's equator—their position with respect to the earth remains fixed. The subpoint of the eastern satellite is at longitude 75° W., and the subpoint of the western satellite is at longitude 135° W. (Reference 11). The satellites have imaging and data-collection capabilities.

The SMS/GOES satellites acquire imagery in the visible (0.55 to 0.75 μm) and thermal infrared (10.5 to 12.6 μm) parts of the spectrum by means of Visible and Infrared Spin Scan Radiometers (VISSRs) (Reference 11). Although these sensors can image almost the entire Earth (full disk) per scanning cycle, sectors of limited and specified geographical areas are extracted for detailed study (Figure 13). The sectorized SMS/GOES visible images have a maximum spatial resolution of 1 km at nadir and are available as frequently as every 30 minutes.

Methods of Analysis

The VISSR imagery produces a distorted view of the surface of the Earth that changes in scale and resolution with increasing distance north and south of the equator. The Zoom Transfer Scope can be used to correct the VISSR imagery and to project it onto watershed maps. The position of the snowline can then be plotted and measurements of snow-covered area can be obtained either by manual or electronic-planimeter methods.

Advantages and Limitations

The main advantage of using the VISSR imagery for snow-cover mapping is that imagery is available as frequently as every 30 minutes. This capability allows afternoon viewing of mountainous areas that may have had fog or mist when imaged in midmorning by the NOAA or Landsat systems. The system also allows the hydrologist to monitor rapidly changing snow-cover distributions and weather systems. A review of current VISSR imagery in Arizona prior to snow-reconnaissance flights provided valuable information that improved not only the efficiency of the missions but the safety of the flights relative to the effects of incoming storms. The main limitations of using the VISSR imagery for snow-cover mapping in Arizona are its low resolution and geometric distortion. Current research by NESS indicates that geometric corrections and measurements of snow-covered area can be obtained by computer processing of the SMS/GOES digital data (R. S. Gird, National Environmental Satellite Service, written commun., 1978).

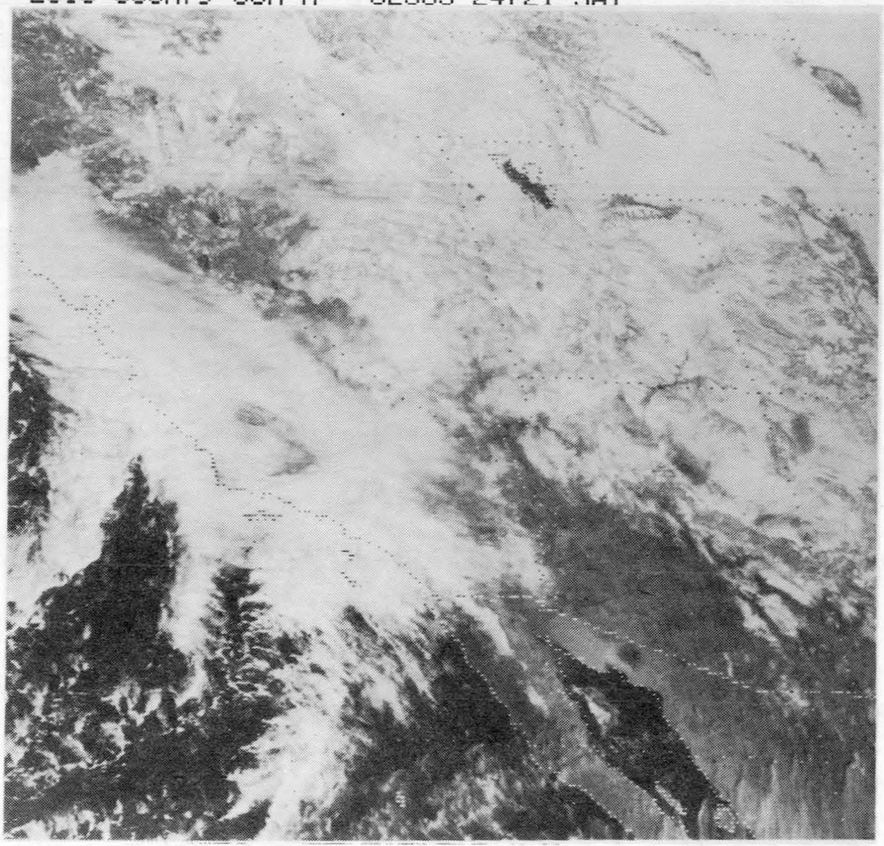

Figure 13. SMS/GOES VISSR image taken in the visible part of the spectrum.

OPERATIONAL APPLICATIONS OF SATELLITE SNOW-COVER OBSERVATIONS

Temporal and areal variations in snow cover are recognized as important hydrologic parameters that are related to snowmelt-derived runoff in Arizona and other parts of the Western United States. The areal extent of snow cover and the average snowpack water equivalent determine the volume of water stored in the snowpack. These properties are highly variable in the mountains in central Arizona and are difficult to determine using conventional ground surveys. Prior to satellite snow-cover observations, frequent low-level reconnaissance flights—sometimes daily—were required to monitor the rapid snow-cover depletion and to assess the potential for additional runoff during periods of rapid snowmelt (Figure 14).

A comparison of satellite and aerial snow-cover observations for Salt River subwatershed 1 indicates that daily observations, such as those provided by the ITOS and SMS/GOES satellites, are necessary for the effective monitoring of rapid and frequent changes in snow cover (Reference 12). The percentage of snow-covered area in Salt River subwatershed 1 and runoff measured at the Black River near Fort Apache gaging station in 1975-76 are shown in Figure 14.

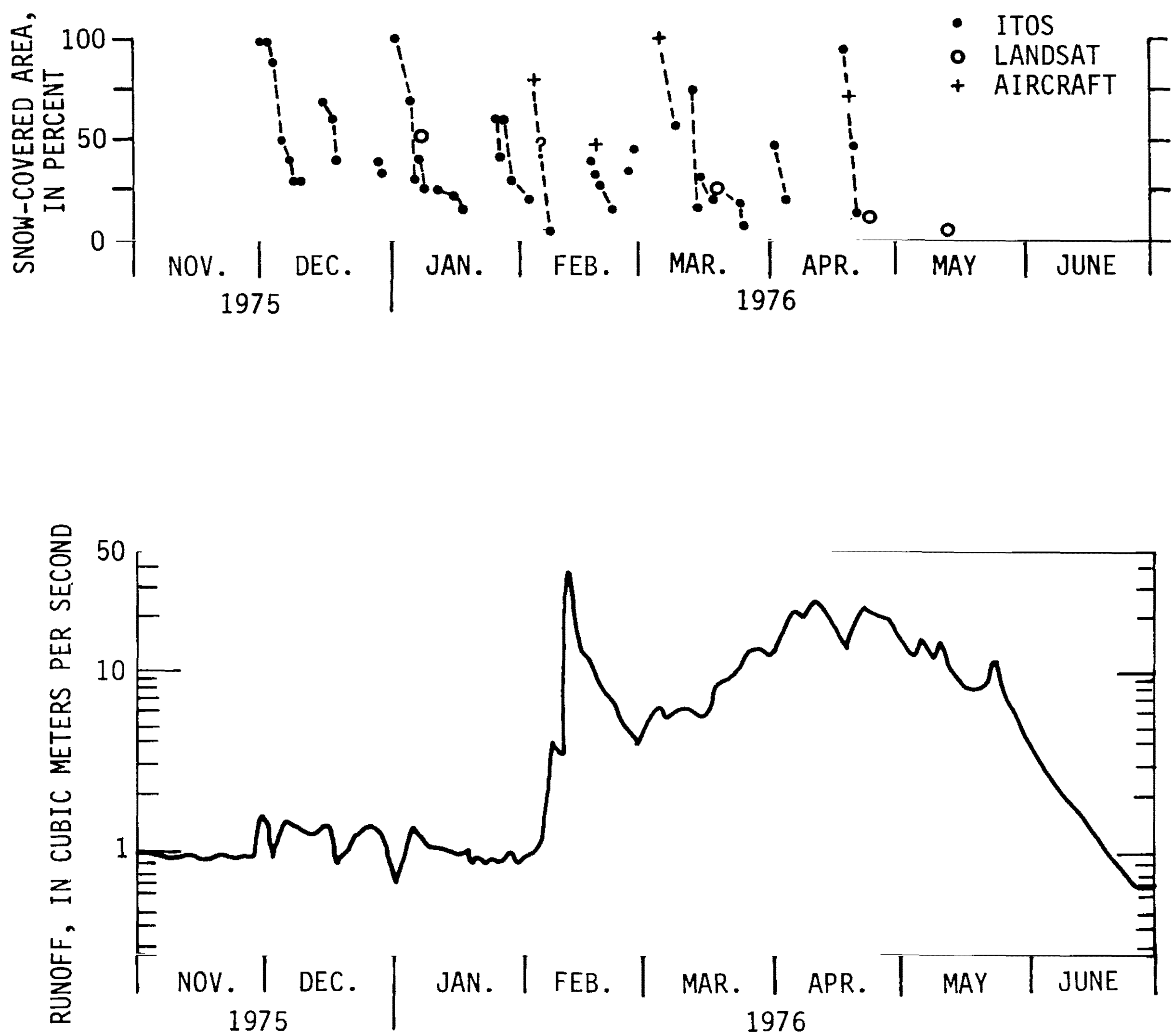

Figure 14. Distribution of snow cover and runoff, Salt River subwatershed 1.

A quasi-operational snow-mapping program was developed by NESS in 1974 (Reference 9). Imagery provided by the ITOS satellites and, more recently, the imagery provided by the SMS/GOES satellites were used by NESS to produce maps showing snow-covered areas during cloud-free periods. The maps are small scale and show the percentage of snow-covered area in the Salt River part and Verde River part of the watershed. The maps include large ungaged areas below the principal forecast points—Verde River below Tangle Creek above Horseshoe Dam and Salt River near Roosevelt gaging stations. The percentage of snow-covered area above each forecast point was determined from the NESS maps and is given in Table 3.

Table 3

Percentage of Snow-Covered Area From Maps by NESS

Date	Snow-covered area, in percent			
	Salt River part of watershed	Salt River above Roosevelt	Verde River part of watershed	Verde River above Tangle Creek
1974				
November 4.......	14	25	19	22
November 7.......	5	8	14	16
November 10......	2	4	3	3
December 7.......	15	25	17	19
December 10......	3	6	11	13
December 15......	2	4	4	5
December 24......	41	56	33	38
December 30......	--	--	25	28
1975				
January 3........	76	91	--	--
January 4........	67	86	31	35
January 5........	40	62	--	--
January 12.......	40	54	36	41
January 14.......	30	40	28	32
January 18.......	9	12	--	--
January 19.......	--	--	17	19
January 20.......	9	13	13	15
January 21.......	--	--	12	14
January 22.......	--	--	10	11
January 25.......	8	13	6	7
February 2.......	21	33	30	34
February 6.......	20	30	27	31
February 8.......	--	--	23	26
February 11......	23	36	24	27
February 12......	17	28	15	17
February 18......	70	89	57	65
February 19......	64	85	55	63
February 23......	43	66	38	43
February 24......	42	62	30	34
February 27......	29	41	22	25
March 1..........	17	28	14	16
March 3..........	17	28	9	10
March 17.........	29	39	33	38
March 19.........	--	--	21	24
March 20.........	14	22	--	--
March 21.........	--	--	15	17
March 24.........	15	26	12	14
March 29.........	--	--	33	38
March 30.........	35	50	27	31
April 3.........	27	39	13	15

Table 3

Percentage of Snow-Covered Area From Maps by NESS—Continued

Date	Snow-covered area, in percent			
	Salt River part of watershed	Salt River above Roosevelt	Verde River part of watershed	Verde River above Tangle Creek
1975—Continued				
April 5.........	13	20	5	6
April 6.........	13	20	--	--
April 16........	16	26	13	15
April 20........	11	19	3	3
April 22........	10	17	4	5
April 24........	9	16	3	3
April 28........	8	15	--	--
April 30........	6	14	--	--
May 1...........	5	11	--	--
May 3...........	4	10	--	--
May 7...........	4	9	--	--
May 13..........	3	7	--	--
November 30.....	82	96	72	82
December 1......	75	95	58	66
December 2......	74	94	44	50
December 3......	61	85	26	30
December 4......	45	71	26	30
December 7......	22	36	18	20
December 8......	20	33	13	15
December 10.....	10	20	9	10
December 15.....	47	66	59	67
December 16.....	--	--	43	49
December 17.....	30	46	37	42
December 18.....	20	31	30	34
December 28.....	20	31	13	15
December 29.....	15	26	13	15
1976				
January 1.......	57	84	18	20
January 2.......	--	--	20	23
January 3.......	50	77	--	--
January 5.......	36	59	9	10
January 6.......	19	30	9	10
January 7.......	12	23	9	10
January 8.......	10	18	9	10
January 11......	8	14	6	7
January 15......	7	13	6	7
January 17......	6	10	6	7
January 21......	6	12	6	7
January 25......	21	32	17	19
January 26......	15	26	13	15

Table 3

Percentage of Snow-Covered Area From Maps by NESS—Continued

Date	Snow-covered area, in percent			
	Salt River part of watershed	Salt River above Roosevelt	Verde River part of watershed	Verde River above Tangle Creek
1976—Continued				
January 27......	15	26	9	10
January 29......	13	22	7	8
February 2......	9	16	5	6
February 7......	Clouds	29	--	--
February 11.....	--	--	29	33
February 17.....	15	21	18	20
February 18.....	13	20	16	18
February 19.....	10	18	14	16
February 22.....	8	15	10	11
February 24.....	9	12	10	11
February 26.....	9	15	10	11
March 9.........	21	32	22	25
March 13........	44	64	12	14
March 14........	13	21	--	--
March 15........	12	20	10	11
March 18........	9	18	8	9
March 20........	8	17	7	8
March 24........	7	14	5	6
March 30........	36	54	--	--
April 1.........	17	26	--	--
April 4.........	7	13	--	--
April 18........	61	78	39	44
April 20........	20	30	21	24
April 21........	7	13	8	9
April 24........	4	8	3	3
November 17.....	2	7	0	0
November 28.....	44	68	5	6
November 29.....	39	62	3	3
November 30.....	23	35	2	2
December 1......	18	28	1	1
December 2......	8	17	1	1
December 4......	7	13	0	0
December 8......	4	8	0	0
1977				
January 4.......	--	--	44	50
January 6.......	58	73	--	--
January 9.......	81	94	53	60
January 10......	58	76	46	52
January 11......	--	--	41	47
January 12......	50	67	--	--
January 13......	14	26	35	40

Table 3

Percentage of Snow-Covered Area From Maps by NESS—Continued

Date	Snow-covered, area in percent			
	Salt River part of watershed	Salt River above Roosevelt	Verde River part of watershed	Verde River above Tangle Creek
1977—Continued				
January 15......	44	63	39	44
January 24......	19	30	23	26
January 28......	19	31	19	22
January 31......	16	24	17	19
February 2......	--	--	15	17
February 3......	15	22	15	17
February 7......	17	26	15	17
February 8......	12	20	12	14
February 10.....	--	--	Clouds	28
February 13.....	13	19	9	10
February 14.....	9	17	8	9
February 15.....	9	18	8	9
February 19.....	5	12	2	2
February 23.....	4	11	--	--
February 26.....	27	39	28	32
February 27.....	14	24	13	15
February 28.....	12	33	12	14
March 2.........	40	62	7	8
March 3.........	12	18	8	9
March 6.........	5	12	4	5
March 30........	38	56	2	2
March 31........	22	33	--	--
April 4.........	48	64	36	41
April 5.........	29	39	24	27
April 6.........	16	25	8	9
April 7.........	15	25	4	5
April 10........	--	--	<1	1
November 8......	--	--	8	9
November 9......	5	13	3	3
1978				
January 2.......	5	10	2	2
January 7.......	4	8	3	3
January 13......	8	15	15	17
January 16......	Clouds	35	--	--
January 18......	Clouds	40	--	--
January 22......	34	51	--	--
January 25......	26	40	29	33
January 26......	22	36	22	25
January 28......	17	32	18	20
February 3......	17	31	16	18

Table 3

Percentage of Snow-Covered Area From Maps by NESS—Continued

Date	Snow-covered, area in percent			
	Salt River part of watershed	Salt River above Roosevelt	Verde River part of watershed	Verde River above Tangle Creek
1978—Continued				
February 16[1]....	77	90	86	98
February 16[2]....	70	83	57	65
February 19.....	48	65	36	41
February 20.....	47	61	35	40
February 21.....	42	57	30	34
February 22.....	27	42	24	27
February 23.....	22	34	22	25
February 25.....	18	28	17	19
March 7.........	15	26	10	11
March 8.........	13	23	9	10
March 14........	31	43	26	30
March 15........	16	25	17	19
March 16........	16	25	11	12
March 20........	16	26	6	7
March 25........	10	19	5	6
March 28........	10	20	2	2
April 3.........	10	20	1	1
April 5.........	8	17	<1	1
April 11........	7	15	<1	1
April 20........	4	9	<1	1

[1]Measurement taken at 0926 local time.
[2]Measurement taken at 1216 local time.

SNOW-COVER DEPLETION AND RUNOFF

The rate at which snow cover is depleted from the watershed can be considered as an index of the volume and rate of runoff that will be generated by snowmelt (Reference 13). As snow begins to melt at the lower altitudes, runoff increases to a peak that is governed by the extent of the ripe snowpack and the amount of thermal energy added to the snowpack. Runoff then begins to recede until the remaining snowpack disappears, the melt rate changes, or additional precipitation occurs.

In the Salt-Verde watershed snow at altitudes above 2,100 m often remains until the snowmelt period—March, April, and May. Snow at altitudes below 2,100 m—the altitude of about 90 percent of the watershed—is ephemeral and is subject to rapid melting induced by sharp increases in temperature or by rain on the snowpack (Reference 3). The combination of rain falling on snow and rising temperatures often produces rapid increases in runoff and creates a large flood potential in the Salt River Valley when reservoirs are filled to near capacity.

In the Salt-Verde watershed the most rapid change in snow cover observed on satellite imagery was on February 16, 1978, after a storm deposited a thin layer of snow over most of the watershed. Snow-cover distributions were mapped from VHRR imagery taken at 0926 hours (local time) and from VISSR imagery taken at 1216 hours (local time). (See Table 3.) In less than 3 hours the snow-covered area decreased 7 percent in the Salt River part of the watershed and 29 percent in the Verde River part of the watershed.

Statistical Analysis

During periods of snow-cover depletion, measurements of snow-covered area often fall along a straight line when the logarithm of snow-covered area is plotted against time in days (Figures 15-22). The relation can be expressed by the linear equation

$$\log S = bt + a, \qquad (1)$$

where S is snow-covered area in percent, t is time in days during the period of snow-cover depletion, and b and a are regression constants.

As few as two consecutive snow-cover measurements can be used to determine a first approximation of the rate of depletion of snow-covered area and to make short-term predictions of the percentage of snow-covered area (S') a few days in the future. Such short-term predictions of S' will be reasonably accurate if additional precipitation does not fall and large changes in air temperature do not occur.

A comparison of the graphs showing snow-covered area and mean daily runoff rates indicates that periods of reduction in snow-covered area often correspond to periods of changes in runoff rates (Figures 15-22). A linear regression analysis was used to determine the relation between snow-covered area and the corresponding runoff rates for 26 events in the Salt River part

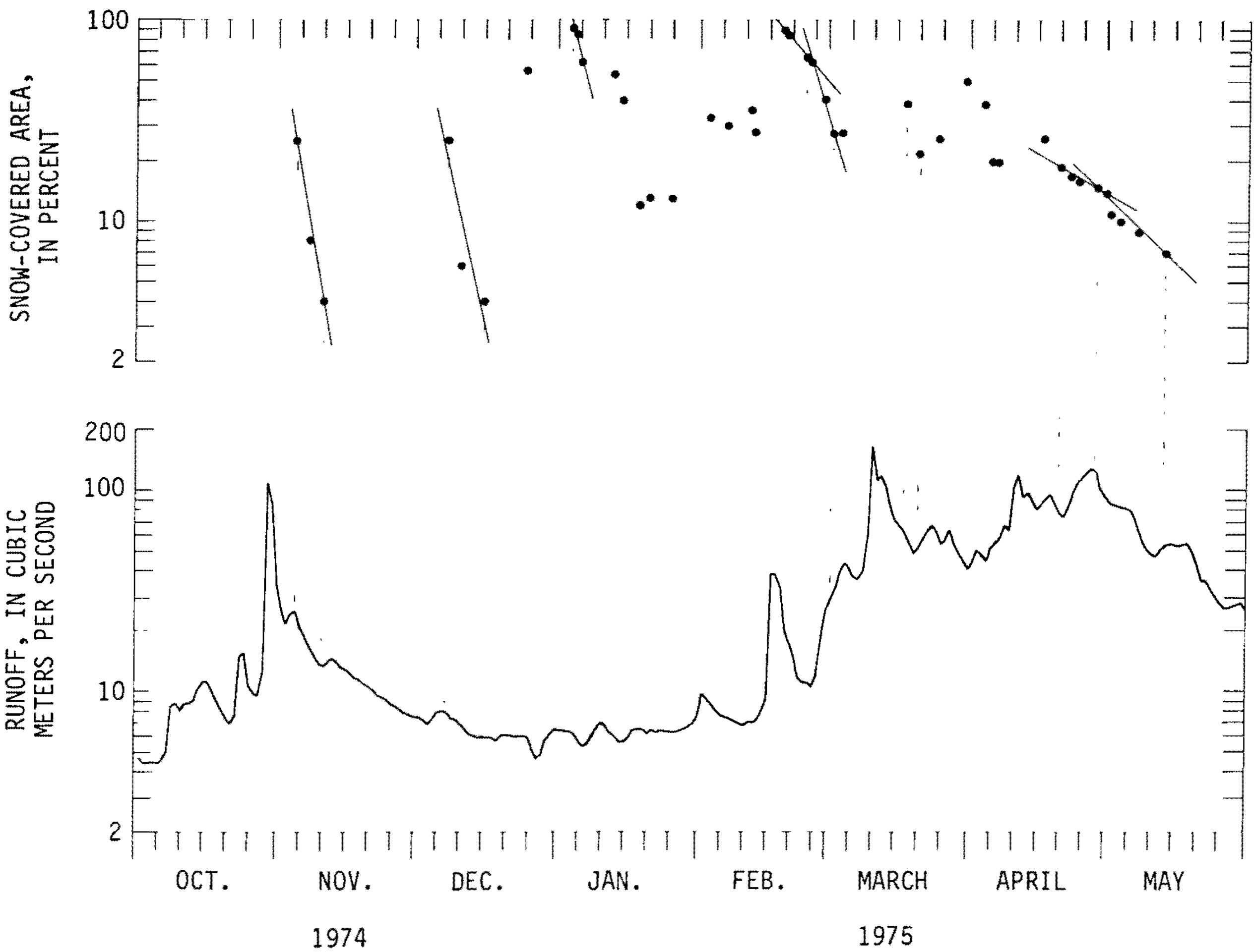

Figure 15. Percentage of snow-covered area and runoff from the Salt River part of the watershed above the Salt River near Roosevelt gaging station, 1974-75.

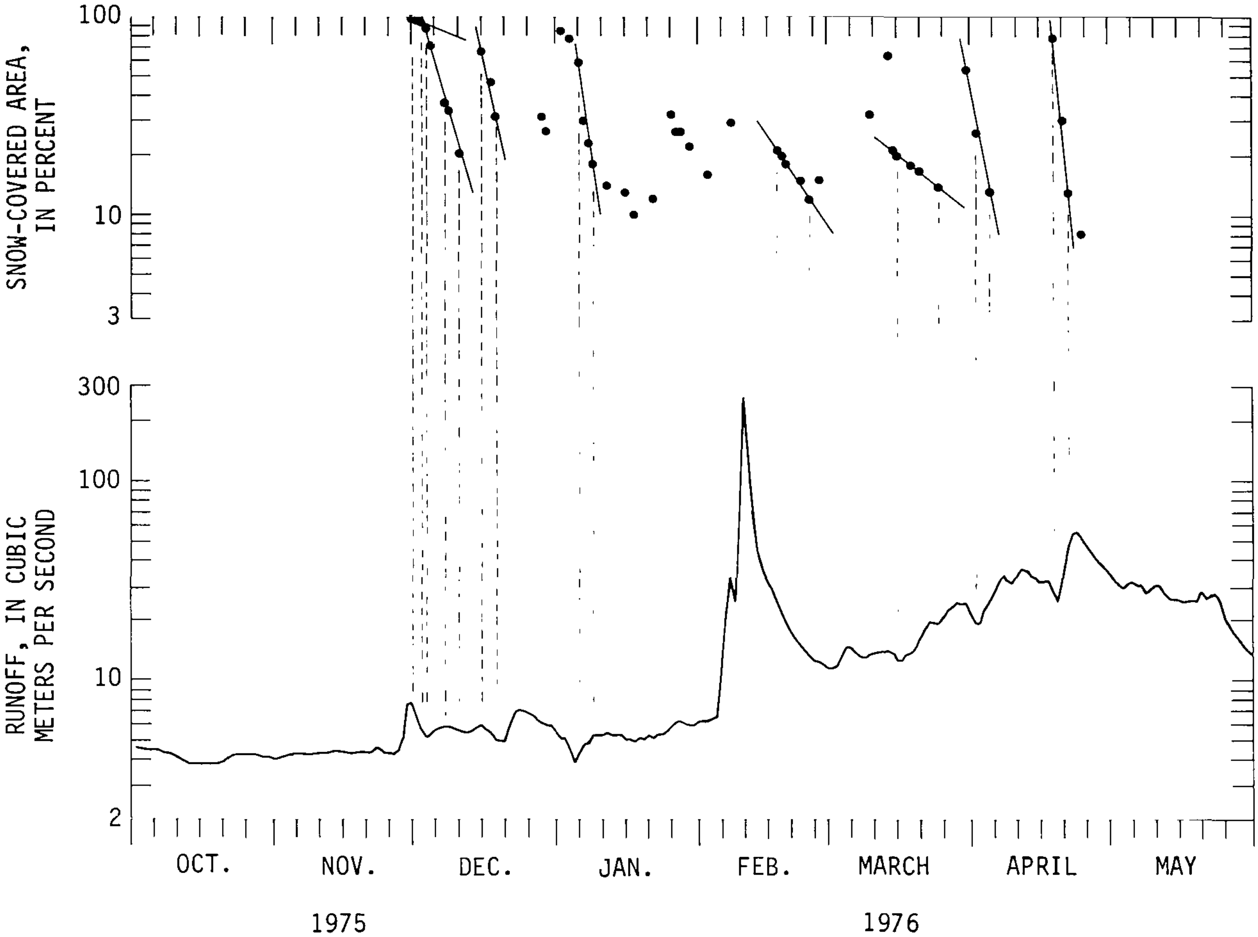

Figure 16. Percentage of snow-covered area and runoff from the Salt River part of the watershed above the Salt River near Roosevelt gaging station, 1975-76.

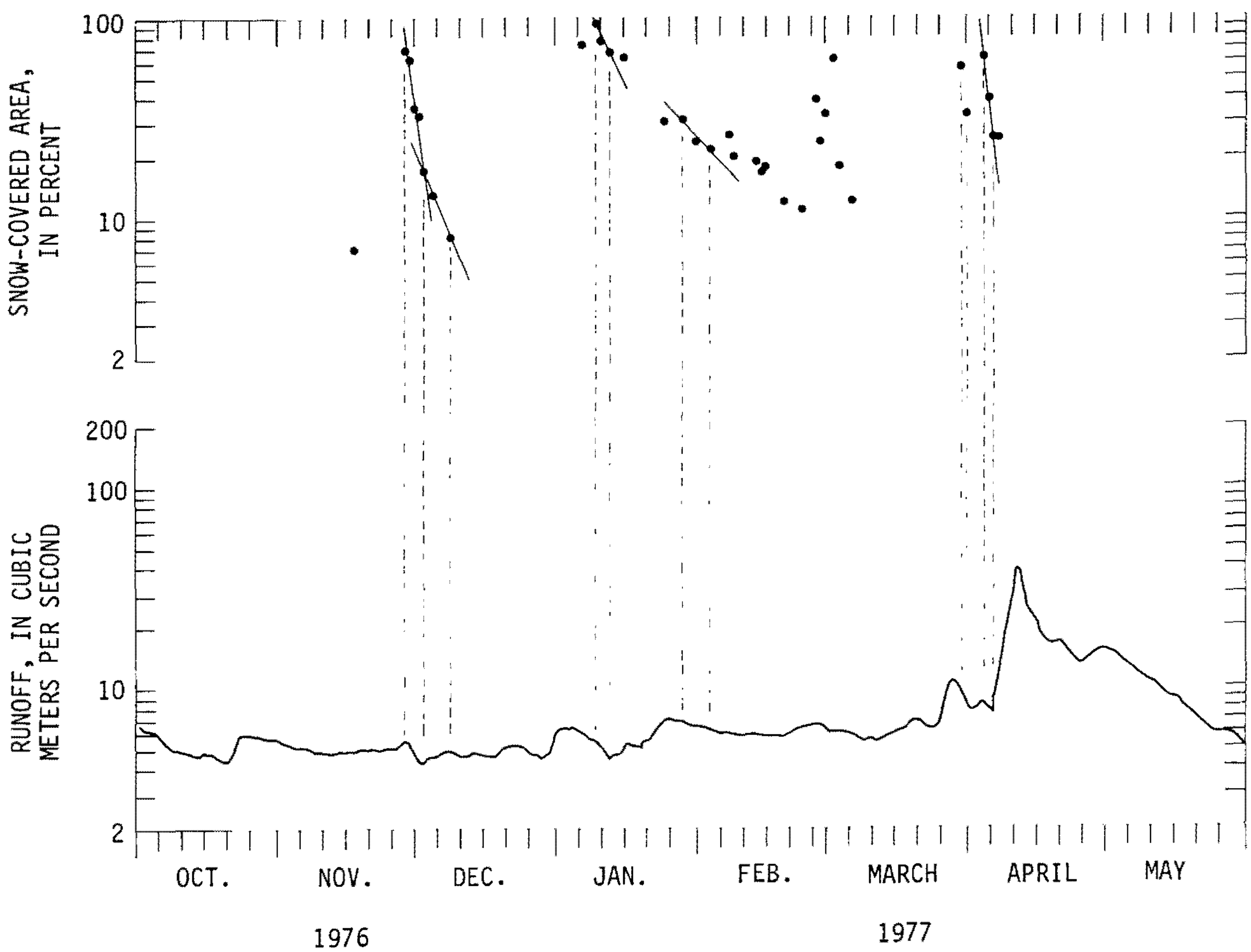

Figure 17. Percentage of snow-covered area and runoff from the Salt River part of the watershed above the Salt River near Roosevelt gaging station, 1976-77.

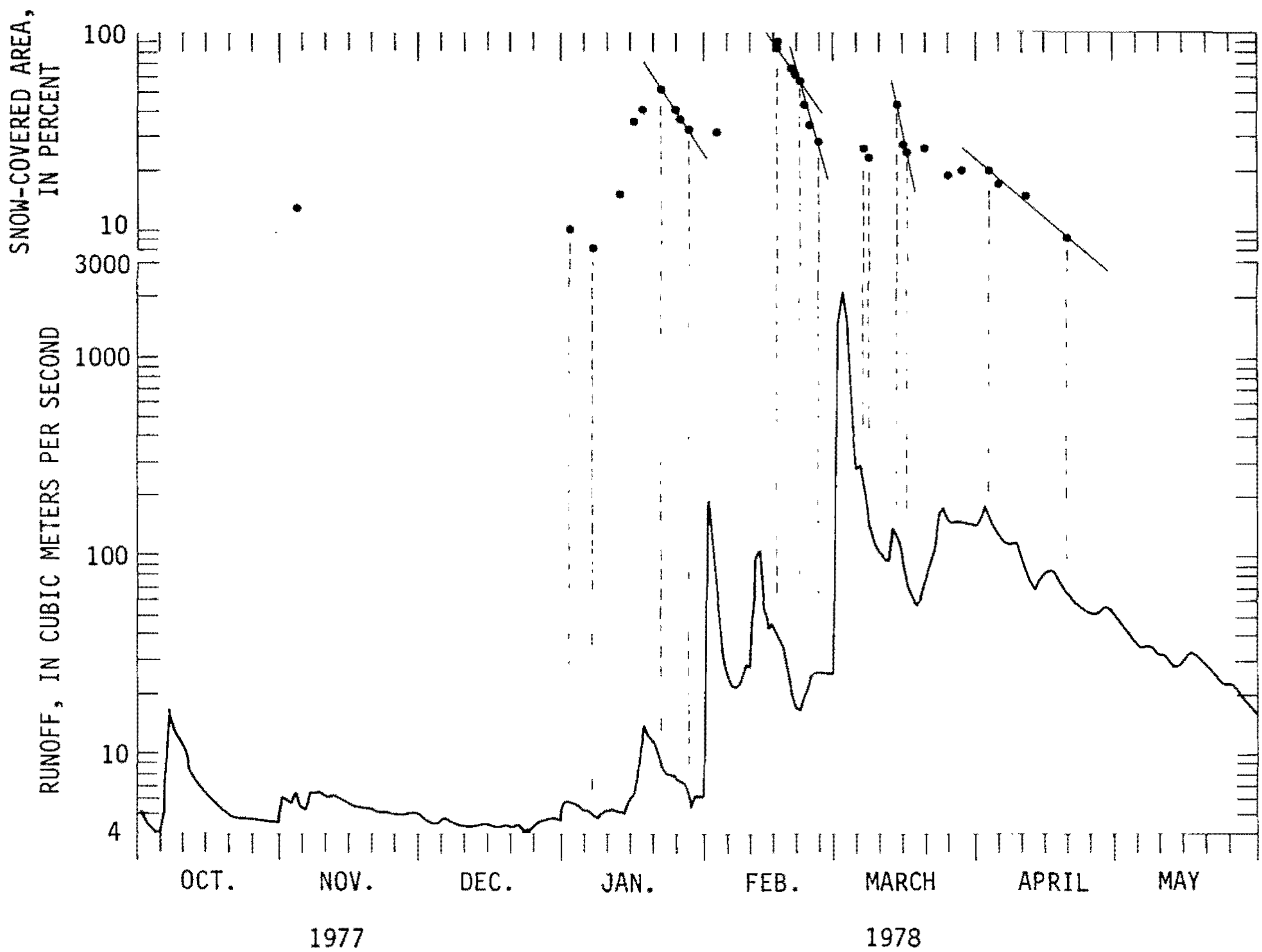

Figure 18. Percentage of snow-covered area and runoff from the Salt River part of the watershed above the Salt River near Roosevelt gaging station, 1977-78.

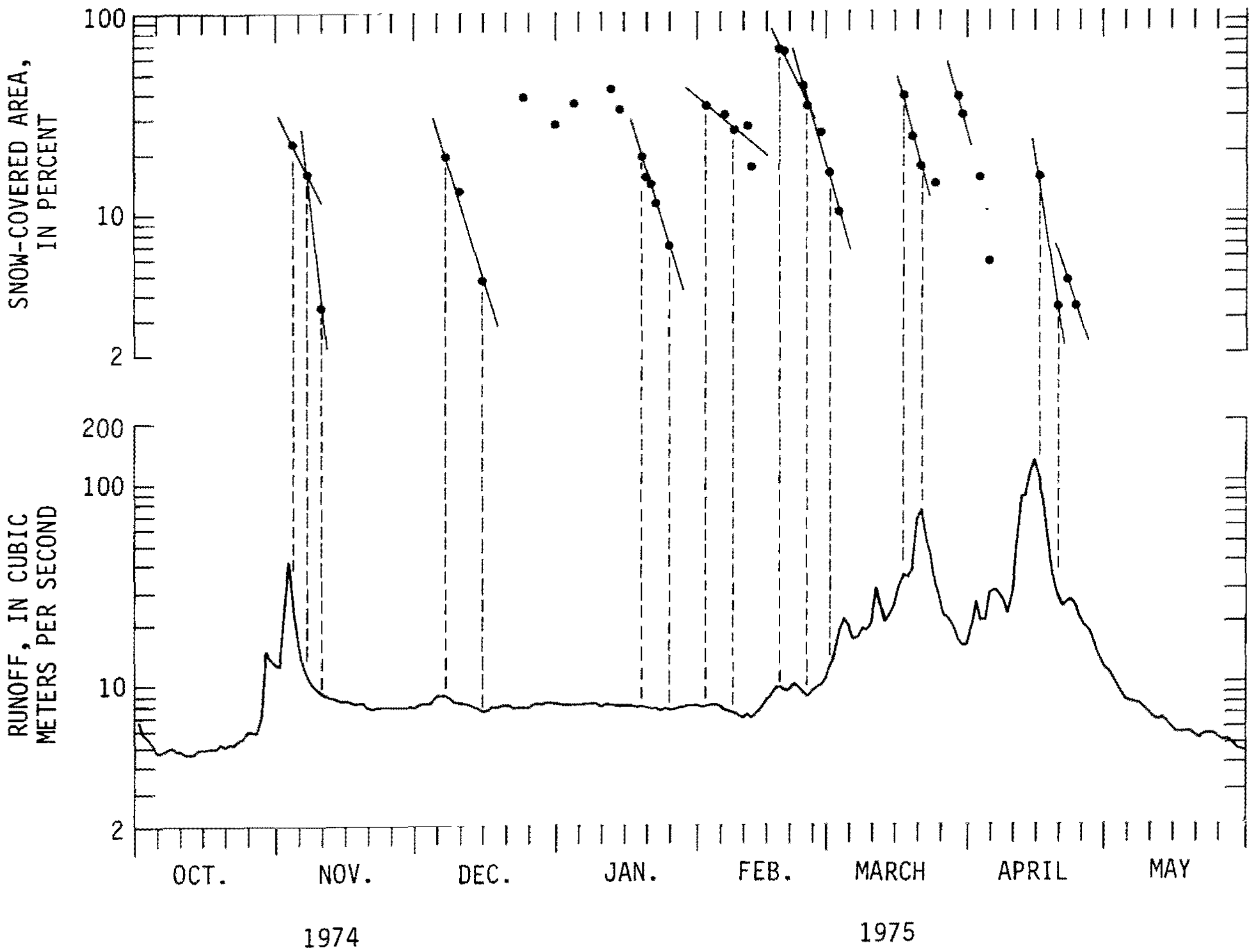

Figure 19. Percentage of snow-covered area and runoff from the Verde River part of the watershed above the Verde River below Tangle Creek, above Horseshoe Dam gaging station, 1974-75.

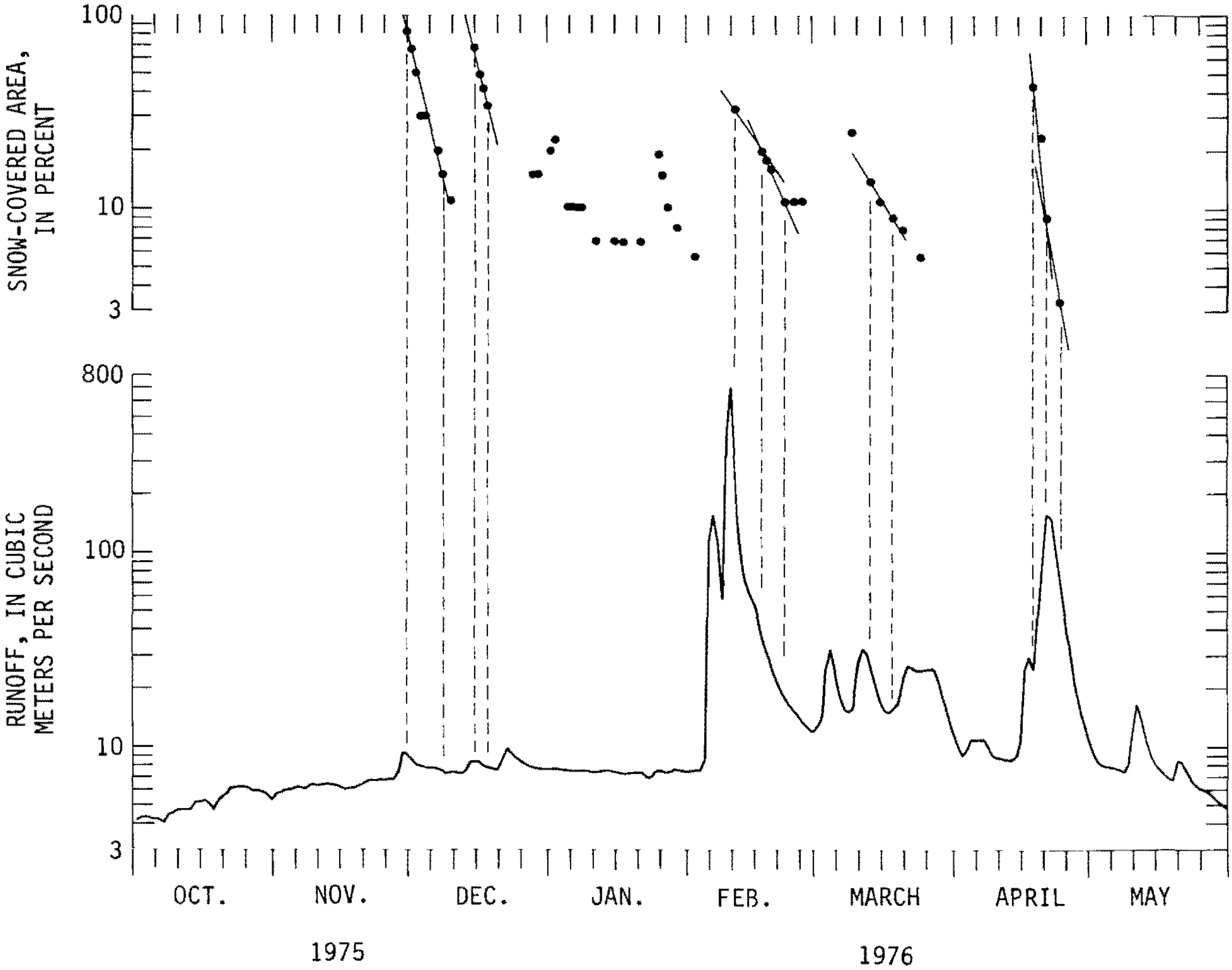

Figure 20. Percentage of snow-covered area and runoff from the Verde River part of the watershed above the Verde River below Tangle Creek, above Horseshoe Dam gaging station, 1975-76.

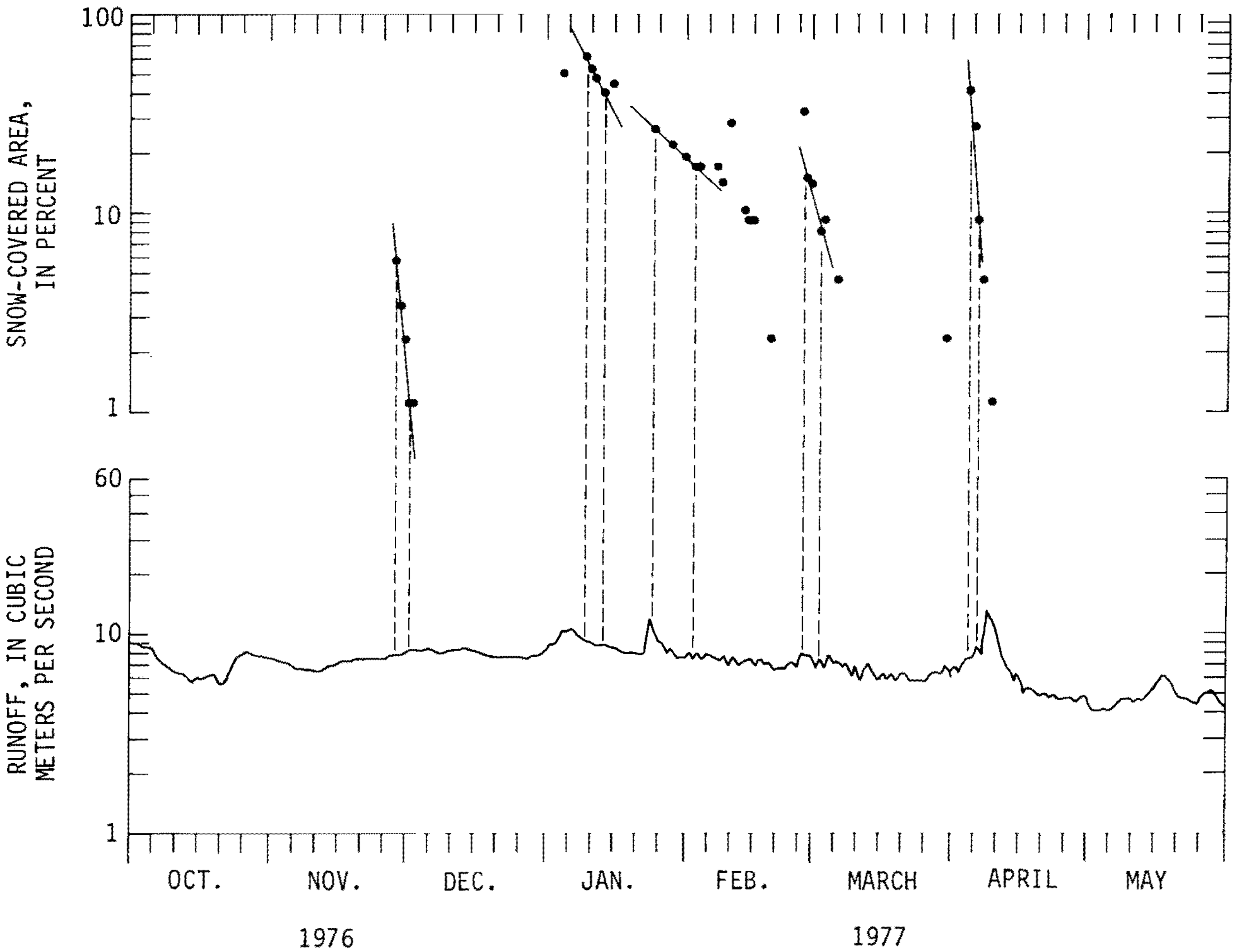

Figure 21. Percentage of snow-covered area and runoff from the Verde River part of the watershed above the Verde River below Tangle Creek, above Horseshoe Dam gaging station, 1976-77.

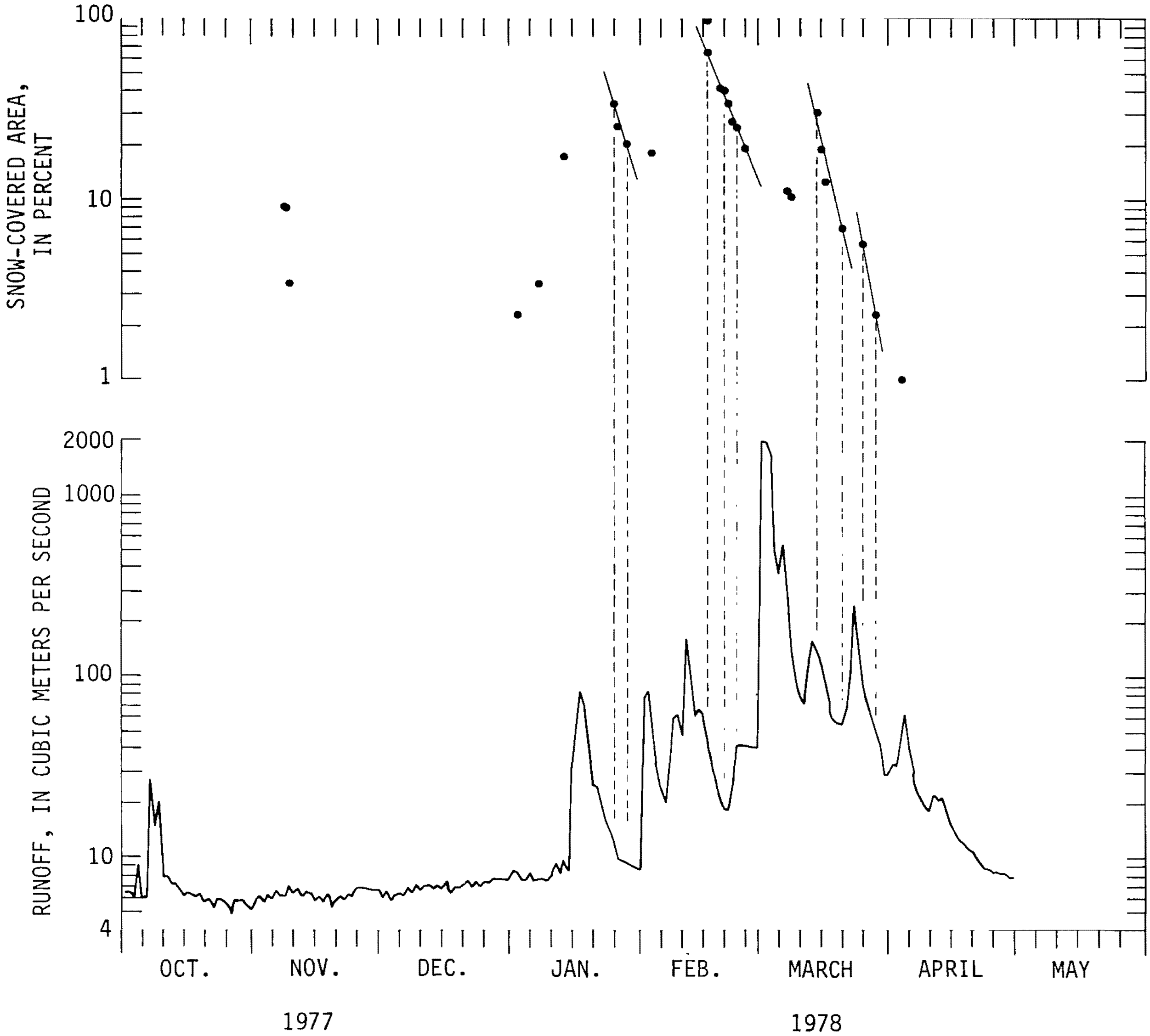

Figure 22. Percentage of snow-covered area and runoff from the Verde River part of the watershed above the Verde River below Tangle Creek, above Horseshoe Dam gaging station, 1977-78.

of the watershed and 22 events in the Verde River part during 1974-78 (Tables 4 and 5). Selected observations of snow-cover depletion, based on three or more consecutive measurements during a single depletion period, were used with corresponding mean daily runoff rates at the principal forecast points on the Salt and Verde Rivers. The percentage of snow-covered area was considered as the independent variable, and the corresponding mean daily runoff was considered as the dependent variable. The simple linear regression equation developed for each event is

$$R = bS + a, \tag{2}$$

where R is the mean daily runoff in cubic meters per second, S is the snow-covered area in percent, b is the regression coefficient or the slope of the regression line, and a is the intercept along the ordinate (Reference 14). If the regression equation describes the relation between variables that are physically related, it can serve as a model to predict other values of the dependent variable.

Early in the winter runoff period—October 1 to February 15—runoff rates often are at or near base-flow levels in the Salt and Verde Rivers, and most of the snowmelt replenishes soil moisture and ground-water storage. During this period, large changes in snow-covered area often result in small measurable changes in runoff rates. For 1974-78, absolute values of b for snow-cover depletion events in the Salt River part of the watershed ranged from 0.01 to 0.15 except during the November 4 to 10, 1974, and November 30 to December 2, 1975, events when b was 0.53 and 1.01, respectively (Table 4). These exceptions were the result of early winter storms that produced more than 50 mm of precipitation in 1 day followed by warming conditions. For 1974-78, absolute values of b for snow-cover depletion events in the Verde River part of the watershed ranged from 0.02 to 0.34, and most values of b were less than 0.15 (Table 5).

In the late winter and spring runoff period—February 15 to May 15—small changes in snow-covered area may result in small to large changes in runoff rates. For 1974-78, absolute values of b ranged from 0.02 to 11.65 in the Salt River part of the watershed. Absolute values of b in excess of 5.6 were observed only in late spring—April and May (Table 4). For 1974-78, absolute values of b ranged from 0.02 to 6.52 in the Verde River part of the watershed. Absolute values of b in excess of 5.6 were observed only during April (Table 5).

The coefficient of determination (r^2) indicates the proportion of variance in the dependent variable (R), which is explained by the independent variable (S). Because the number of measurements per snow-cover depletion event was small—3 to 7 per event—it was necessary to use the Student's t test to estimate the confidence levels for the r^2 values obtained for the regression equations. Confidence levels ranged from more than 60 percent to more than 99 percent for all snow-cover depletion events (Tables 4 and 5). Although only a small number of measurements was available for each event, the coefficients of determination and confidence levels indicate a strong relation between changes in snow-cover depletion and mean daily runoff rates in the Salt-Verde watershed.

Table 4

Regression Analysis of Snow-Covered Area and Mean Daily Runoff in the Salt River Part of the Watershed, 1974-78

n: Number of measurements.

$\bar{R}$: Arithmetic mean of runoff, in cubic meters per second.

σ_R: Standard deviation of runoff values.

b: Regression coefficient or the slope of the regression line.

a: Intercept along the ordinate.

r^2: Coefficient of determination.

r_{test}: Confidence level.

S_R : Standard error of the estimate.

$\bar{S}_R$: Standard error of the estimate adjusted for the size of the sample.

$\bar{S}_R\%$: Standard error of the estimate expressed as a percent of the mean.

Event	Snow cover, in percent		n	$\bar{R}$	σ_R	b	a	r^2	r_{test}	S_R	$\bar{S}_R\%$
	Maximum	Minimum									
WINTER RUNOFF PERIOD OF 1974-75 Runoff Decreasing											
Nov. 4-10, 1974.........	25	4	3	18.26	6.02	0.53	11.68	0.98	90	0.73	7
Dec. 7-15, 1974.........	25	4	3	6.86	.98	.08	5.96	.83	>70	.39	10
Jan. 3-5, 1975..........	91	62	3	5.99	.34	.02	4.26	+.99	>95	.02	.45
Feb. 18-23, 1975........	89	66	3	20.75	10.56	.76	-40.57	.80	70	4.76	40
Apr. 28-May 13, 1975....	15	7	6	82.24	23.41	7.31	1.82	.90	>95	7.39	11
WINTER RUNOFF PERIOD OF 1974-75 Runoff Increasing											
Feb. 24-Mar. 1, 1975....	62	28	3	19.66	9.13	-0.39	34.80	0.69	>60	5.10	45
Mar. 30-Apr. 5, 1975....	50	20	3	46.76	3.78	-.244	55.61	.95	>80	.84	3.1
Apr. 20-28, 1975........	19	15	4	102.80	19.88	-11.65	290.90	.86	86	7.45	10
WINTER RUNOFF PERIOD OF 1975-76 Runoff Decreasing											
Nov. 30-Dec. 2, 1975....	96	94	3	6.55	1.01	1.01	-87.86	+0.99	95	0.06	1.5
Dec. 7-10, 1975.........	36	20	3	5.74	.16	.02	5.18	.97	>80	.03	.88
Dec. 15-18, 1975........	66	31	3	5.43	.48	.03	4.14	+.99	>95	.01	.30
Feb. 17-24, 1976........	21	12	5	18.79	4.79	1.26	-2.94	.96	>99	.95	6.6
WINTER RUNOFF PERIOD OF 1975-76 Runoff Increasing											
Dec. 3-7, 1975..........	85	36	3	5.43	0.34	-0.01	6.30	0.99	95	0.03	1.1
Jan. 5-8, 1976..........	59	18	4	4.76	.42	-.02	5.46	.87	87	.15	4.5
Mar. 15-24, 1976........	20	14	4	15.20	2.94	-1.15	35.06	.95	95	.64	6.0
Apr. 18-21, 1976........	78	13	3	40.52	14.90	-.45	58.32	+.99	95	.76	3.2
WINTER RUNOFF PERIOD OF 1976-77 Runoff Decreasing											
Nov. 28-Dec. 2, 1976....	68	17	5	4.82	0.59	0.03	3.72	0.97	>99	0.10	2.6
Jan. 9-12, 1977.........	94	67	3	4.98	.50	.03	2.48	.76	>60	.25	8.4
Jan. 28-Feb. 3, 1977....	31	22	3	6.41	.25	.05	5.10	.91	>70	.08	2.0
Apr. 4-6, 1977..........	64	25	3	7.90	.45	.02	6.94	.96	>80	.09	1.9
WINTER RUNOFF PERIOD OF 1976-77 Runoff Increasing											
Dec. 2-8, 1976..........	8	4	3	4.51	0.34	-0.15	5.43	0.91	>70	0.10	3.8
WINTER RUNOFF PERIOD OF 1977-78 Runoff Decreasing											
Jan. 22-28, 1978........	51	32	4	7.20	1.34	0.14	1.57	0.75	75	0.67	13
Feb. 16-21, 1978........	90	57	4	23.47	11.17	.76	-27.55	.99	>99	1.18	7.1
Mar. 14-16, 1978........	43	25	3	98.00	23.24	2.24	26.85	.91	>70	7.03	12
Apr. 3-20, 1978.........	20	9	4	105.00	40.04	8.18	-17.81	.92	92	11.31	15
WINTER RUNOFF PERIOD OF 1977-78 Runoff Increasing											
Feb. 21-25, 1978........	30	17	4	21.62	4.09	-0.70	38.05	0.87	87	1.48	9.7

Table 5

Regression Analysis of Snow-Covered Area and Mean Daily Runoff in the Verde River Part of the Watershed, 1974-78

n: Number of measurements.

$\bar{R}$: Arithmetic mean of runoff, in cubic meters per second.

σ_R: Standard deviation of runoff values.

b: Regression coefficient or the slope of the regression line.

a: Intercept along the ordinate.

r^2: Coefficient of determination.

r_{test}: Confidence level.

S_R : Standard error of the estimate.

$\bar{S}_R$: Standard error of the estimate adjusted for the size of the sample.

$\bar{S}_R\%$: Standard error of the estimate expressed as a percent of the mean.

Event	Snow cover, in percent		n	$\bar{R}$	σ_R	b	a	r^2	r_{test}	S_R	$\bar{S}_R\%$
	Maximum	Minimum									
WINTER RUNOFF PERIOD OF 1974-75 Runoff Decreasing											
Dec. 7-15, 1974.........	19	5	3	7.73	0.67	0.10	6.55	0.99	95	0.06	1.2
Jan. 11-25, 1975........	19	7	5	7.22	.11	.02	6.89	.94	>95	.03	.48
Feb. 2-8, 1975..........	34	26	3	7.08	.27	.06	5.12	.95	80	.06	1.5
Feb. 18-24, 1975........	65	34	4	8.65	.39	.02	7.39	.90	90	.12	2.0
Apr. 16-24, 1975........	15	3	4	42.36	36.93	6.52	.67	.99	99	3.70	12
WINTER RUNOFF PERIOD OF 1974-75 Runoff Increasing											
Feb. 24-Mar. 3, 1975....	34	10	4	11.56	3.89	0.34	18.82	0.85	85	1.51	19
Mar. 17-21, 1975........	38	17	3	45.16	20.3	-1.48	84.53	.62	>60	12.52	48
WINTER RUNOFF PERIOD OF 1975-76 Runoff Decreasing											
Nov. 30-Dec. 8, 1975....	82	15	7	7.76	0.59	0.02	6.80	0.96	>99	0.11	1.7
Dec. 15-18, 1975........	67	34	4	7.78	.28	.02	6.89	.85	85	.11	2.0
Feb. 17-22, 1976........	20	11	4	26.54	7.67	1.96	-5.52	.98	98	1.01	5.4
Mar. 13-18, 1976........	14	9	3	18.37	4.73	1.76	-1.76	.90	>70	1.51	14
WINTER RUNOFF PERIOD OF 1975-76 Runoff Increasing											
Mar. 15-20, 1976........	20	17	3	13.94	1.93	-1.15	35.22	0.83	>70	0.78	9.9
Apr. 18-21, 1976........	44	9	3	86.41	64.51	-3.64	173.80	.98	90	9.13	18
WINTER RUNOFF PERIOD OF 1976-77 Runoff Decreasing											
Jan. 9-13, 1977.........	60	40	4	8.90	0.22	0.02	7.64	0.96	96	0.06	0.71
Jan. 24-Feb. 2, 1977....	26	17	4	8.43	1.32	.34	1.63	.93	93	.50	5.9
Feb. 27-Mar. 2, 1977....	15	8	3	7.53	.27	.06	6.72	.88	>70	.16	2.2
WINTER RUNOFF PERIOD OF 1976-77 Runoff Increasing											
Nov. 28-Dec. 1, 1976....	5.7	1	4	7.76	0.22	-0.10	8.06	0.73	73	0.17	2.2
Apr. 4-6, 1977..........	41	9	3	7.78	.59	-.04	8.68	.91	>70	.30	4.0
WINTER RUNOFF PERIOD OF 1977-78 Runoff Decreasing											
Jan. 25-28, 1978........	33	20	3	10.05	1.43	0.22	4.48	0.96	>80	0.48	4.8
Feb. 16-20, 1978........	98	40	3	64.40	18.93	.56	30.41	+.99	99	.70	1.9
Mar. 14-20, 1978........	30	7	4	97.72	35.78	3.42	39.45	.91	91	15.12	15
WINTER RUNOFF PERIOD OF 1977-78 Runoff Increasing											
Mar. 21-25, 1978........	34	19	4	31.02	11.23	-1.62	73.33	0.79	79	7.34	24

Values obtained for the standard error of estimate (S_R) must be adjusted for the number of measurements when the number of measurements is small (Reference 14). Values of the standard error of estimate in Tables 4 and 5 were adjusted using the equation

$$\bar{S}_y^2 = S_y^2 \frac{n}{n-2}, \qquad (3)$$

where S_y is the standard error of estimate, and n is the number of measurements per event (Reference 14). The adjusted standard error of estimate divided by the arithmetic mean of the runoff rate ranged from 0.30 to 45 and averaged 8.7 percent in the Salt River part of the watershed (Table 4) and ranged from 0.48 to 48 and averaged 8.9 percent in the Verde River part of the watershed (Table 5).

Short-Term Runoff Predictions

Equation 1 may be used with equation 2 to predict mean daily runoff rates if no large changes in runoff conditions occur during the prediction period. The volume of short-term runoff can be calculated by summation of the estimates of mean daily runoff using the equation

$$V = (\bar{R}'_1 + \bar{R}'_2 + \bar{R}'_3 + \ldots + \bar{R}'_n)\ (0.0864) \qquad (4)$$

where V is the volume of runoff in cubic hectometers, $\bar{R}'_1$ to $\bar{R}'_n$ are the predicted mean daily runoff rates in cubic meters per second, and 0.0864 is a constant that converts the mean daily runoff rate into cubic hectometers.

Table 6 gives examples of runoff predictions using equation 4. Example 1 gives data for the Salt River part of the watershed in January of the early winter runoff period when large changes in snow-covered area resulted in small changes in runoff rates. Data collected on January 22 and 25 were used to estimate the percentage of snow-covered area (S') and the mean daily runoff rate for January 26. Data collected on January 22, 25, and 26 were then used to estimate S' and $\bar{R}'$ for January 27 and 28. When measured snow-covered area differs significantly from the estimated snow-covered area, a new snowcover depletion and runoff relation must be developed before new runoff predictions are made.

In example 2, data collected on April 11 and 20 of the late winter runoff period were used to estimate S' and $\bar{R}'$ for the next 5-day period. The accuracy of the runoff predictions decreased as the time since the last measurement of snow-covered area and measured mean daily runoff increased. The estimated volume of runoff was about 8 percent larger than the measured volume of runoff (Table 6).

Seasonal Runoff Predictions

In the Salt River Valley surface-water supplies were extremely variable prior to the completion of Theodore Roosevelt Dam—in 1911—and the other five dams that constitute the Salt-Verde reservoir system. In most years the reservoir

Table 6

Comparison of Measured and Estimated Snow-Covered Area and Mean Daily Runoff Values, Salt River Part of the Watershed

Δt: Time in days since first snow-cover measurement.
S: Measured snow-covered area, in percent.
S': Estimated snow-covered area, in percent.
$\bar{R}$: Measured mean daily runoff, in cubic meters per second.
$\bar{R}'$: Estimated mean daily runoff, in cubic meters per second.
$\bar{R}/\bar{R}'$: Ratio of measured to estimated mean daily runoff.
Δ%: Difference between measured and estimated mean daily runoff rate, in percent.

Day	Δt	S	S'	$\bar{R}$	$\bar{R}'$	$\bar{R}/\bar{R}'$	Δ%
Example 1, January 1978							
22	0	51	----	8.43	-----	----	----
25	3	40	----	7.76	-----	----	----
26	4	36	36.8	7.25	7.56	0.96	4
27	5	--	33.3	6.58	7.14	.92	8
28	6	32	30.6	6.10	6.94	.88	12
Volume of runoff, in cubic hectometers				1.72	1.87	.92	8
Example 2, April 1978							
11	0	14	----	80.08	-----	----	----
20	9	9	----	63.28	-----	----	----
21	10	--	8.6	59.36	61.94	0.96	4
22	11	--	8.2	57.12	60.59	.94	6
23	12	--	7.8	54.32	59.25	.92	8
24	13	--	7.4	51.80	57.90	.89	11
25	14	--	7.0	50.40	56.56	.89	11
Volume of runoff, in cubic hectometers				23.59	25.60	.92	8.0

system controls the flow of the Salt and Verde Rivers and provides water, hydroelectric power, and limited flood protection. The accurate prediction of runoff into the reservoir system is important to the economy of the Salt River Valley. Seasonal runoff predictions are estimated to produce average annual benefits of more than $11 million to users of runoff for irrigation in the Salt River Project area (Reference 15).

Seasonal runoff predictions require careful consideration of many hydrologic parameters, such as antecedent precipitation and runoff amounts and basin storage; basin storage includes soil moisture, ground water in storage, and the volume and distribution of water stored in the snowpack. The probability of postprediction precipitation and energy exchange, which may affect snowmelt and evapotranspiration rates, also should be considered. These parameters are difficult to measure and monitor in areas as large as the Salt-Verde watershed. As a result, index methods often are used to describe moisture conditions for use in making seasonal runoff predictions.

Operational Runoff Predictions

The Salt River Project made the first operational runoff predictions in the Salt-Verde watershed in the early 1930's, when spring runoff was estimated using periodic snow-accumulation reports (Reference 16). In the late 1930's cooperative snow surveys were started by the U.S. Soil Conservation Service and the Salt River Project. The information collected on snow depth, snow water content, and precipitation amounts became operational forecast parameters in the cooperative bimonthly forecast; antecedent precipitation and runoff, ambient air temperature above freezing, sky-cover index, and wind speed at selected sites also are used in the forecast (Reference 16). The runoff equations are based on a multiple linear regression analysis of these variables and the corresponding runoff volumes. The equations provide reasonably accurate runoff predictions for years of low to average runoff volumes; however, the equations rely strongly on averages and have greatly underestimated the large runoff volumes in recent years.

Hydrometeorological Model

Several snowmelt-runoff models were reviewed for use in making winter runoff estimates for the Salt-Verde watershed. A concern for the apparent large changes in basin storage early in the winter runoff season led to the testing of the Hydrometeorological Model (HM) developed by the U.S. Geological Survey in an attempt to improve runoff predictions. The model implicitly incorporates snow, soil moisture, and ground water in storage as a part of basin storage (Reference 17). Derivation of predictive equations and operation of the model are described in detail in earlier publications (References 17, 18, and 19), and only a brief description of the operation of the model is given in this paper. According to Tangborn (Reference 17), the basic assumptions used in the model are:

1. The catch of a low-altitude precipitation gage is proportional to the precipitation on a nearby mountain basin.

2. Temporary basin storage, which includes snow, ground water, and soil moisture, is about equal to the cumulative precipitation less the runoff that has occurred during the precipitation period.

3. Runoff subsequent to the day for which storage is calculated is proportional to the amount of storage on that day.

4. The prediction error in a short-term test prediction—before the main seasonal prediction—is closely related to the error in calculating basin storage, and this relation can be used to reduce the error in the main seasonal prediction.

Optimum use of the model requires that a short-term test prediction be made for the period immediately preceding the main prediction to improve the estimate of basin storage. The error in the test prediction is used to adjust the seasonal prediction. The net effect of precipitation and evaporation losses during the prediction period is considered to be a constant (Reference 17).

Selections of the precipitation gages and the lengths of test predictions used in the model were determined by making retrospective predictions for a large number of years prior to the current predictions. Precipitation records from 49 precipitation gages operated by the U.S. National Weather Service or their cooperators in and near the Salt-Verde watershed were tested to determine those that would enable the most accurate runoff predictions for the three main drainage basins in the watershed. The tests included calculating monthly values of precipitation and runoff for use in the model. Most stations had periods of missing record, which were estimated from records from nearby stations.

Seasonal runoff predictions for the March 1 to May 31 runoff periods for 1960-75 were developed using monthly precipitation and runoff values. The

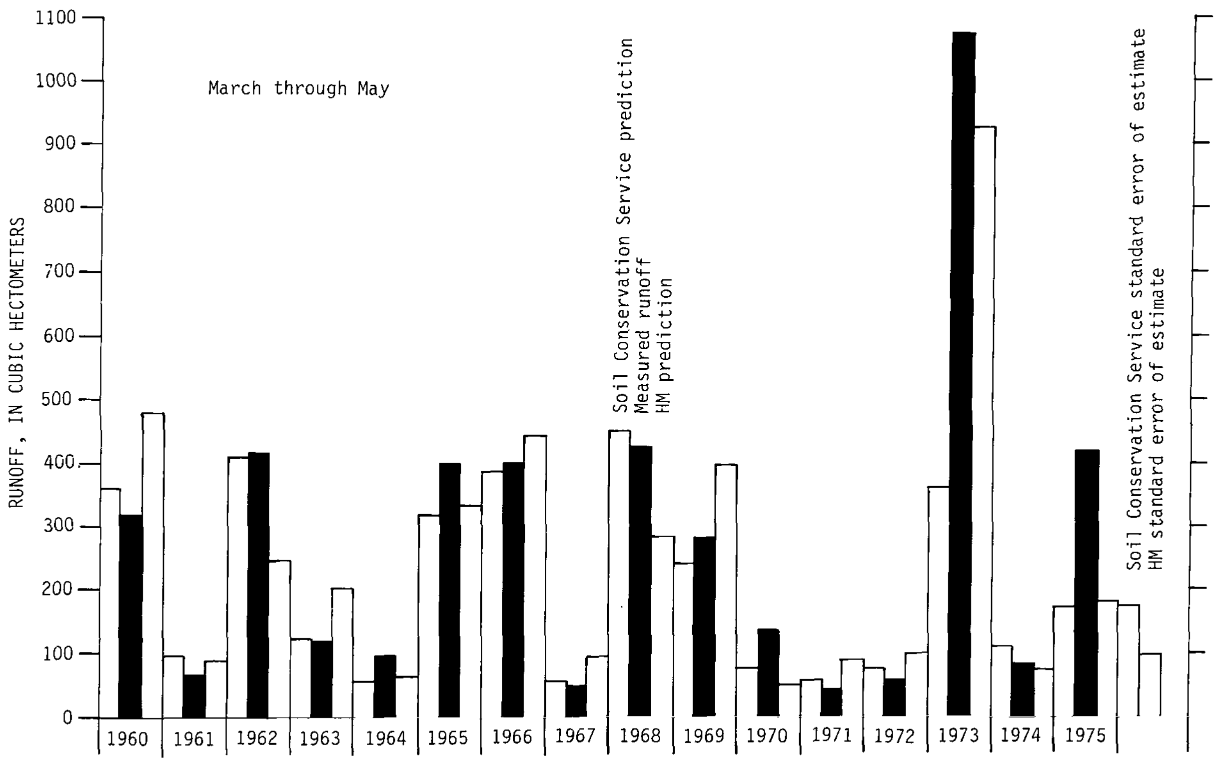

Figure 23. Seasonal runoff predictions, Salt River near Roosevelt.

HM model predictions, Soil Conservation Service forecasts, and measured runoff volumes are compared in Figures 23, 24, and 25 and in Tables 7, 8, and 9. Comparisons of the standard error of estimate for these predictions indicate a reduction in the overall standard error of 42 percent for the Salt River, 46 percent for the Verde River, and 29 percent for Tonto Creek. The comparisons suggest that the HM model can be used to make reasonable estimates of seasonal runoff from the Salt-Verde watershed; however, the HM runoff predictions for individual seasons were less accurate than the operational Soil Conservation Service predictions for 10 of the 16 years tested on the Salt River and Tonto Creek and for 9 of the 16 years tested on the Verde River (Tables 7, 8, and 9). The HM model furnished a more accurate prediction in spring of 1973, when record runoff volumes produced critical water-management problems in central Arizona.

As a result of the tests, the HM model was modified to incorporate mean daily runoff and daily precipitation values and was tested using data for the Verde River. The use of these values improved the accuracy of the runoff predictions for the Verde River by about 57 percent (Figure 26). The modification of the HM model also enabled predictions at any time and for any length of season. The accuracy of the predictions made by the HM model before January 1 was poor. Coefficients of determination for seasonal runoff predictions for Salt River near Roosevelt range from 0 in early December to 0.90 in late March (Figure 27).

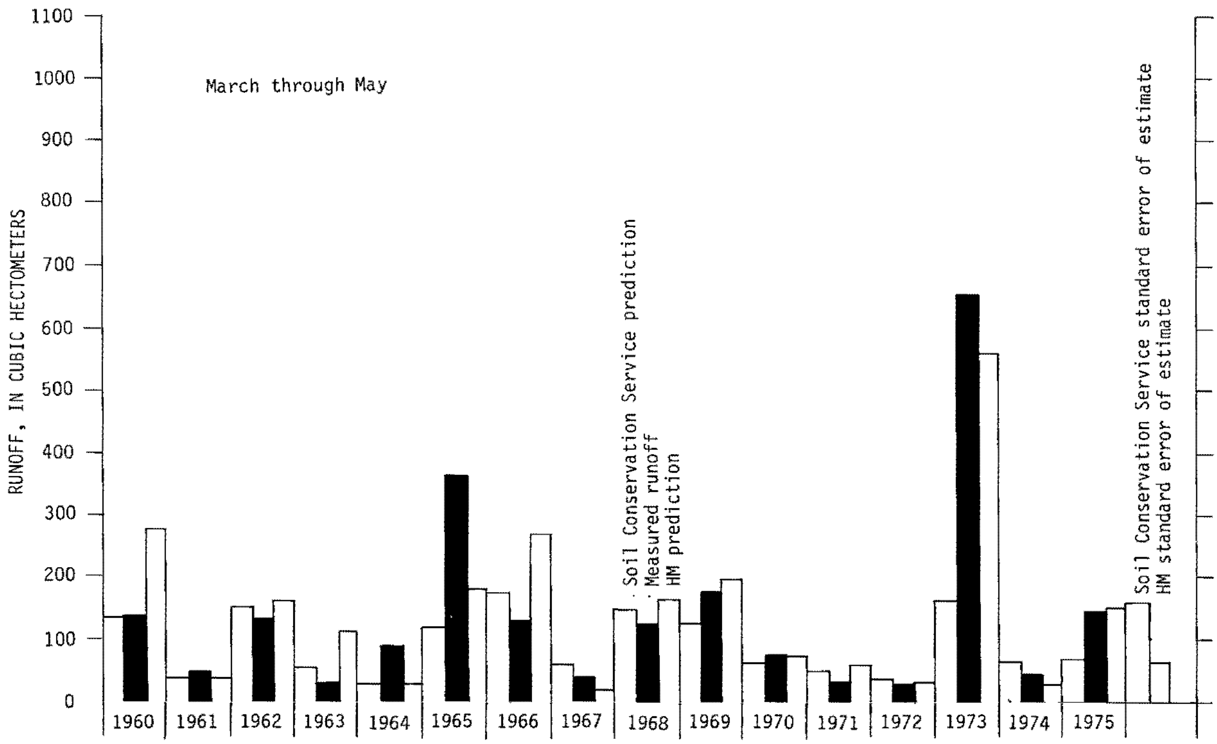

Figure 24. Seasonal runoff predictions, Verde River below Tangle Creek, above Horseshoe Dam.

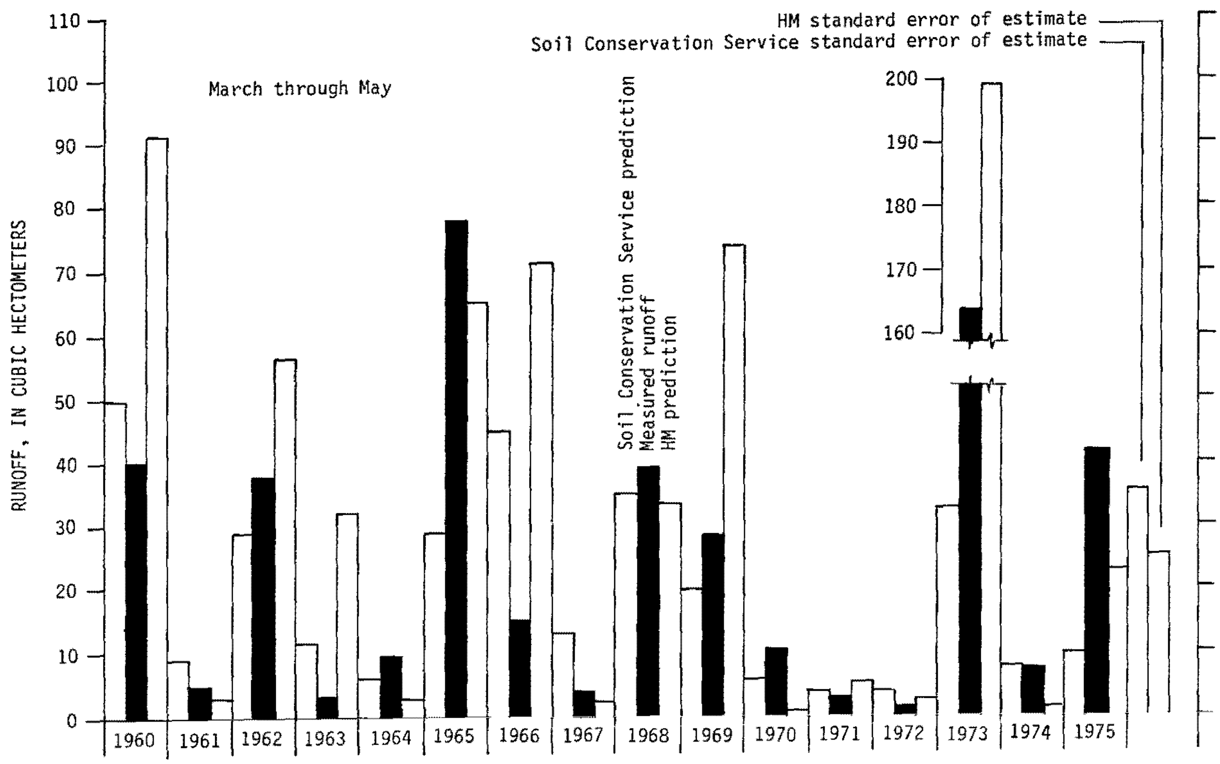

Figure 25. Seasonal runoff predictions, Tonto Creek above Gun Creek, near Roosevelt.

Table 7

Seasonal Runoff Predictions, Salt River Near Roosevelt

Year	March through May runoff, in cubic hectometers				
	Measured	Hydrometeorological model prediction[1]	Prediction error	Soil Conservation Service prediction	Prediction error
1960	395	593	198	444	49
1961	79	110	31	117	38
1962	514	303	-211	506	-8
1963	147	249	102	148	1
1964	115	75	-40	68	-47
1965	490	411	-79	388	-102
1966	493	546	53	475	-18
1967	58	116	58	68	10
1968	522	346	-176	555	33
1969	345	487	142	296	-49
1970	165	60	-105	92	-73
1971	52	110	58	68	16
1972	68	122	54	92	24
1973	1,320	1,140	-180	444	-876
1974	102	89	-13	136	34
1975	513	219	-294	210	-303
Mean	336				
Standard error of estimate			137		236
Standard error of estimate divided by the mean			0.41		0.70
Coefficient of variation	0.936				

[1]Precipitation gage at Beaver Creek Ranger Station.

Table 8

Seasonal Runoff Predictions, Verde River Below Tangle Creek, Above Horseshoe Dam

Year	March through May runoff, in cubic hectometers				
	Measured	Hydrometeorological model prediction[1]	Prediction error	Soil Conservation Service prediction	Prediction error
1960	172	344	172	166	-6
1961	58	48	-10	49	-9
1962	166	201	35	179	13
1963	38	142	104	67	29
1964	111	37	-74	36	-75
1965	450	224	-226	148	-302
1966	161	335	174	216	55
1967	49	25	-24	74	25
1968	156	206	50	185	29
1969	220	246	25	157	63
1970	97	95	-2	80	-17
1971	45	76	31	62	17
1972	39	42	3	49	10
1973	808	691	-117	203	-605
1974	55	36	-19	80	25
1975	182	185	3	86	-96

Mean	175				
Standard error of estimate			96		179
Standard error of estimate divided by the mean			0.55		1.02
Coefficient of variation	1.09				

[1]Average for precipitation gages at Chino Valley and Beaver Creek Ranger Stations.

Table 9

Seasonal Runoff Predictions, Tonto Creek Above Gun Creek, Near Roosevelt

Year	March through May runoff, in cubic hectometers				
	Measured	Hydrometeorological model prediction[1]	Prediction error	Soil Conservation Service prediction	Prediction error
1960	50	113	63	62	12
1961	6	3	-3	11	5
1962	46	70	24	36	-10
1963	4	40	36	14	10
1964	12	3	-9	7	-5
1965	95	80	-15	36	-59
1966	19	88	69	55	36
1967	5	3	-2	16	11
1968	48	41	-7	43	-5
1969	35	91	56	25	-10
1970	13	1	-12	7	-6
1971	4	7	3	5	1
1972	2	3	1	5	3
1973	202	244	42	41	-161
1974	9	2	-7	10	1
1975	52	28	-24	12	-40

Mean	38				
Standard error of estimate			32.2		45.5
Standard error of estimate divided by the mean			0.85		1.20
Coefficient of variation	1.31				

[1]Average for precipitation gages at Chino Valley and Beaver Creek Ranger Stations.

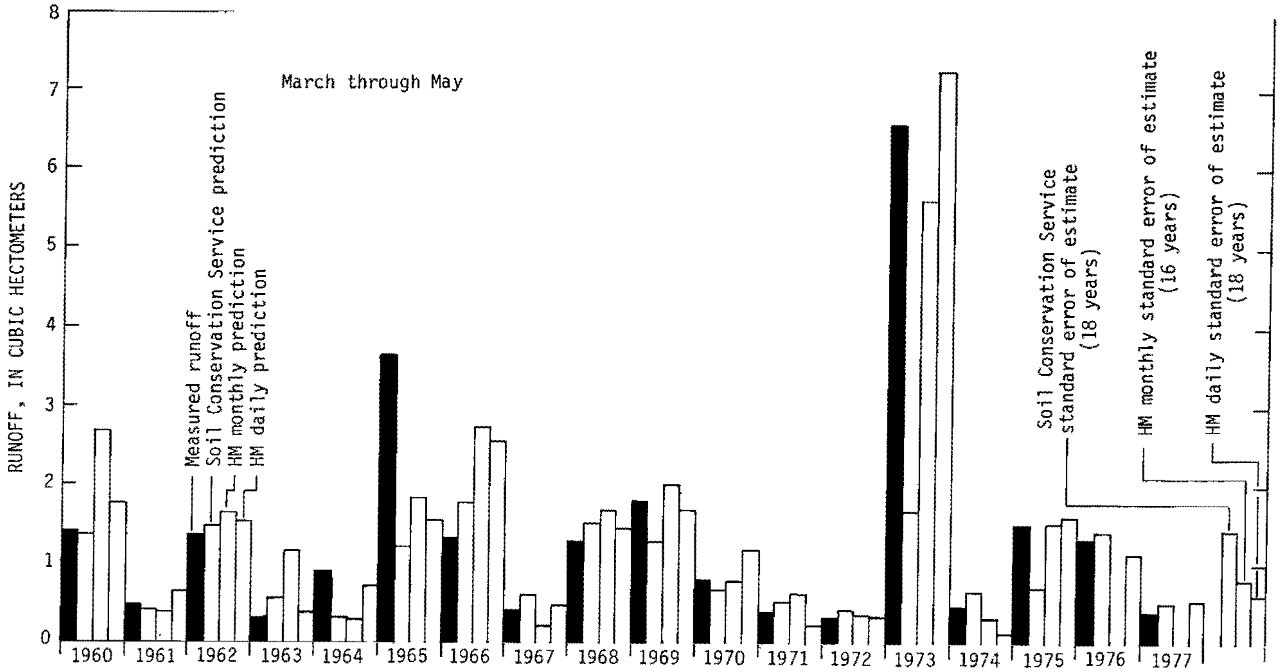

Figure 26. Seasonal runoff predictions, Verde River below Tangle Creek.

The HM model was used to calculate seasonal basin storage for wide ranges of precipitation (Figure 28). In 1973 the above-average basin storage resulted from large amounts of seasonal precipitation; in 1977 the below-average basin storage resulted from small amounts of seasonal precipitation.

The inclusion of mean daily air temperatures in the HM model resulted in a 22-percent accuracy improvement for the April 16-30 short-term runoff prediction for subwatershed 1 (W. V. Tangborn, U.S. Geological Survey, written commun., 1978). In addition to mean daily air temperatures, a radiation or cloud-cover component derived from the range in mean daily air temperatures was included.

Attempts to incorporate snow-covered area measurements in the HM model were unsuccessful. Additional research is needed to allow the effective use of snow-covered area measurements in seasonal runoff predictions. Snow-covered area measurements and information of the areal distribution of snow-water equivalents may provide valuable additional information for use in making seasonal runoff predictions on the Salt-Verde watershed.

TELEMETRY OF HYDROMETEOROLOGICAL DATA

Rapid changes in winter runoff rates in response to rainfall and snowmelt present serious water-management problems in central Arizona. Telemetry systems are used to relay hydrometeorological data from selected sites in the Salt-Verde watershed to assist in the operation of multipurpose reservoirs and to provide flood-warning information. The systems include microwave telemetry, two satellite telemetry systems, and a meteor-burst communication system (Figure 29).

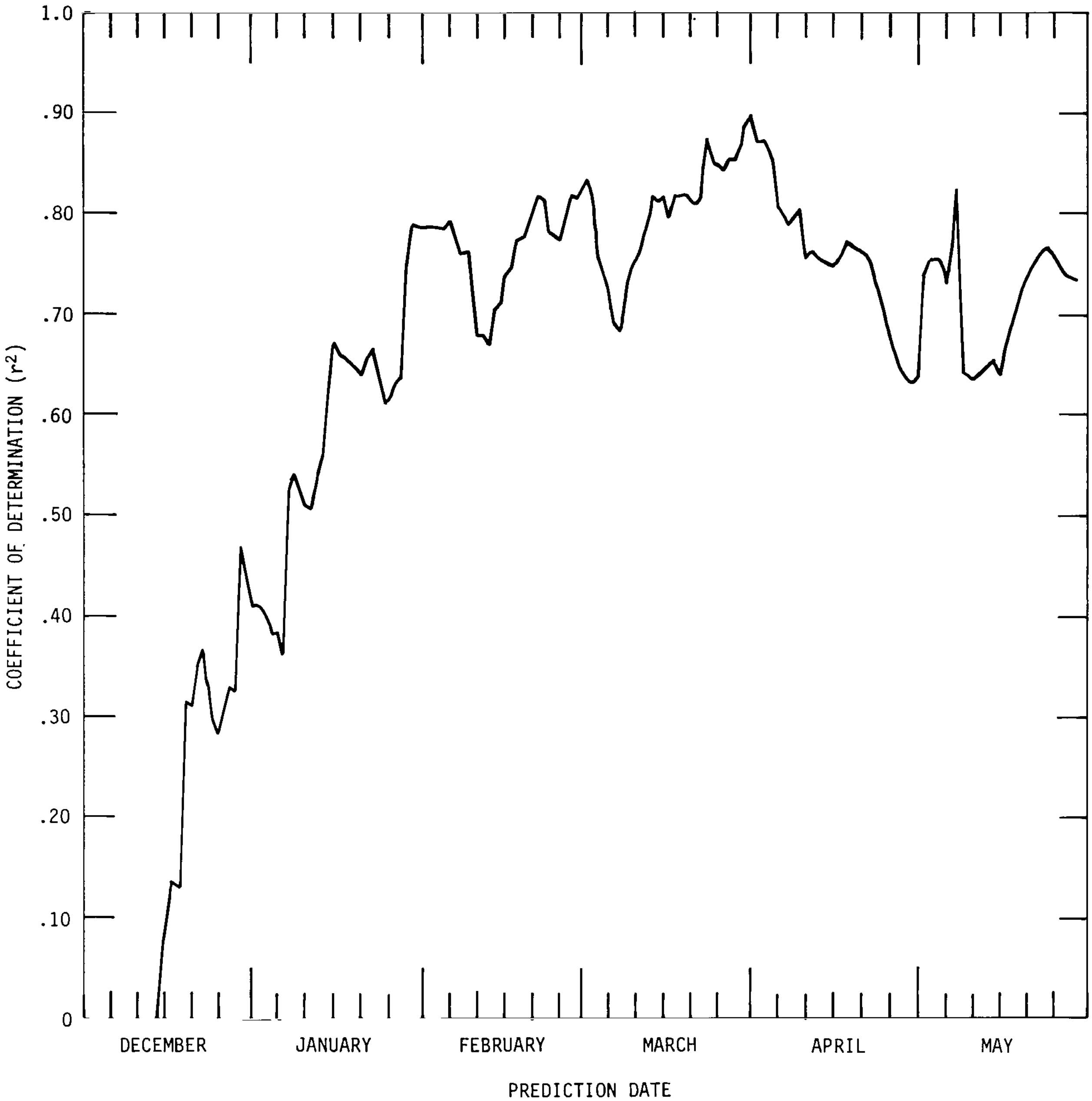

Figure 27. Accuracy of runoff predictions as a function of prediction date, Salt River near Roosevelt.

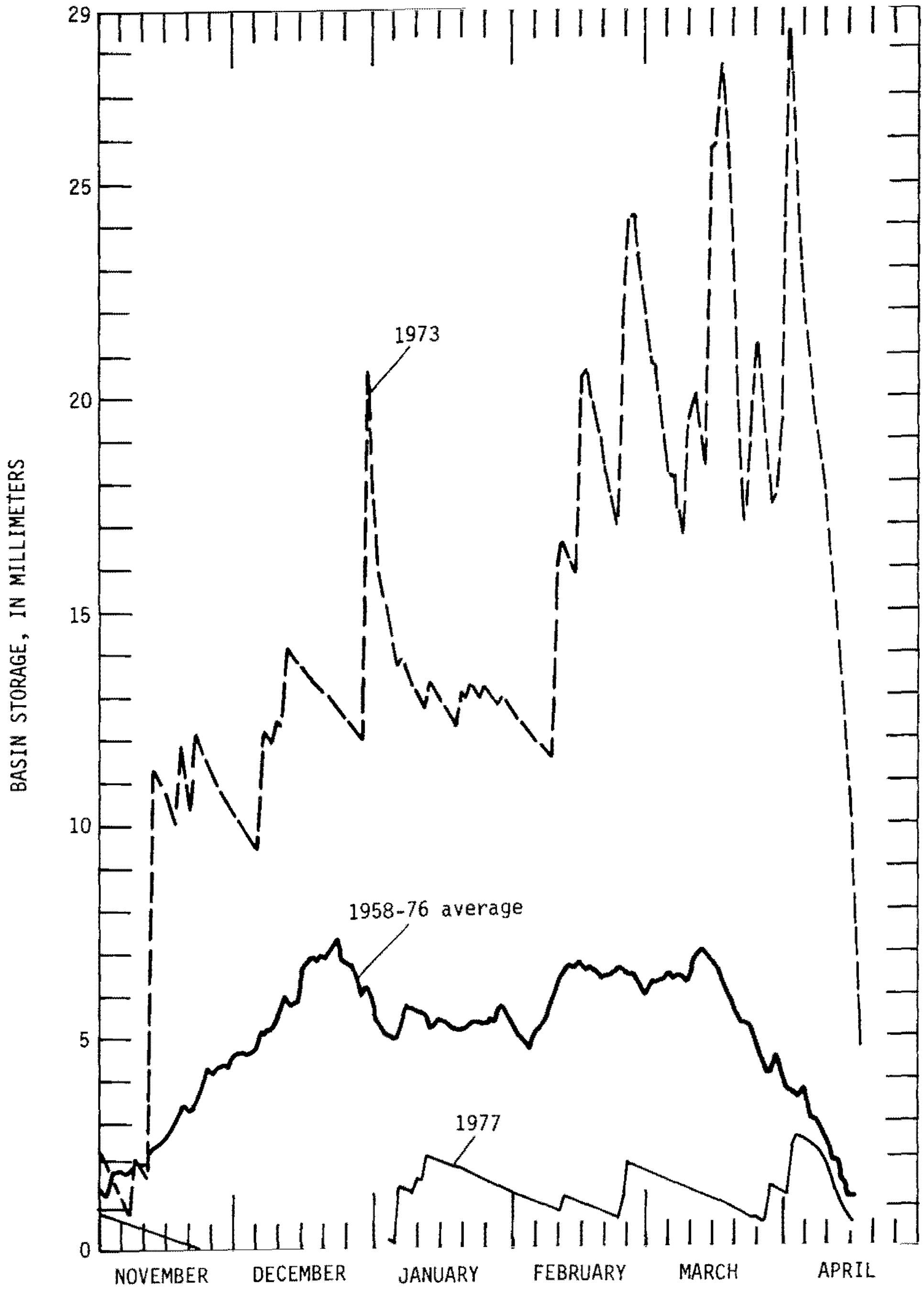

Figure 28. Basin storage in Salt River part of the watershed above the gaging station near Roosevelt for selected periods.

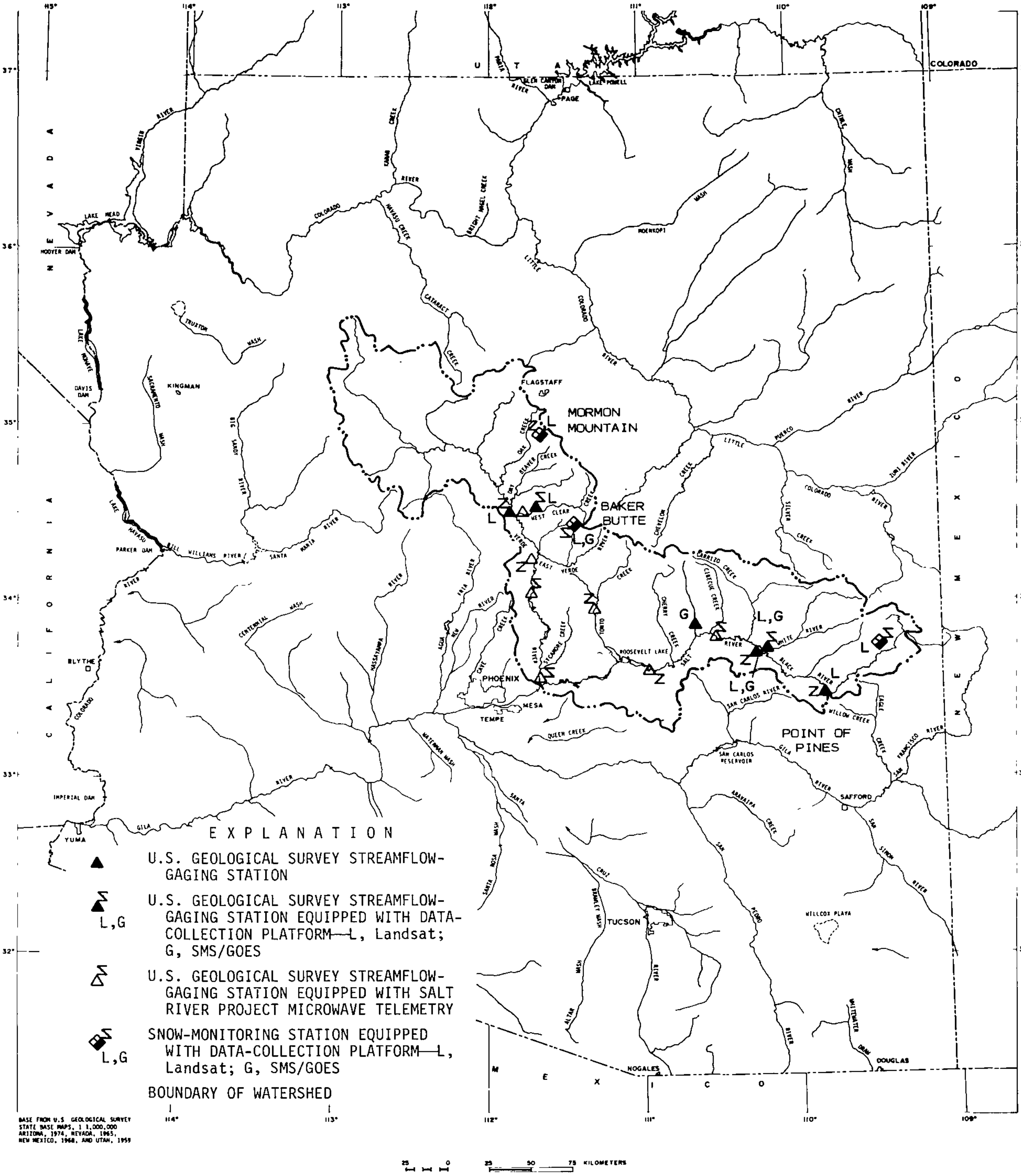

Figure 29. Location of satellite and microwave data-collection systems.

Microwave Telemetry System

The Salt River Project operates a terrestial microwave telemetry system to monitor runoff rates at seven key gaging stations above the reservoirs (Figure 29). The system can be interrogated, and the desired data can be obtained in real time. The main disadvantage of this type of system is the high cost of equipment and maintenance.

Landsat Data-Collection System

During 1972-76, the experimental Landsat data-collection system (DCS) was successfully tested to relay hydrometeorological data from selected streamflow-gaging stations and snow-monitoring sites (Reference 4). The Landsat DCS used battery-powered data-collection platforms (DCPs) to relay hydrometeorological data from remote sites via the Landsat satellites to one or more of the ground-receiving sites in California, Maryland, and Alaska (Figure 30). The Landsat DCPs transmitted as many as 64 bits of data every 90 or 180 seconds to relay data from anywhere in North America during at least two orbits per day—one at about 9:30 in the morning and one at about 9:30 in the evening. When the satellite was in mutual view of a transmitting DCP and one of the ground-receiving sites, the satellite relayed the transmission in real time to the ground-receiving site (Reference 5).

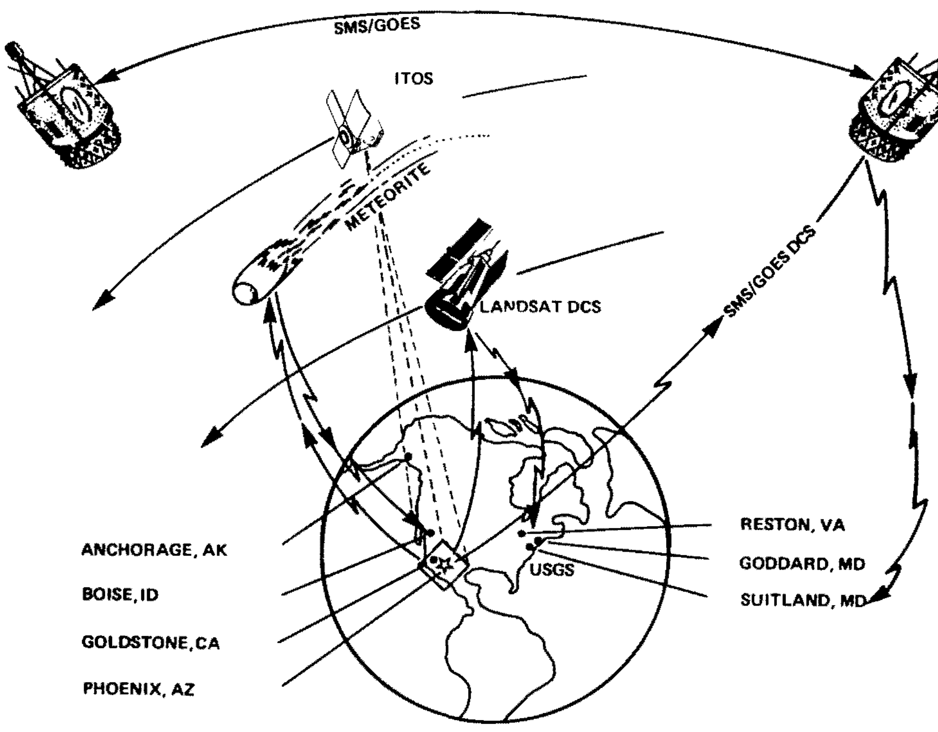

Figure 30. Space telemetry systems.

The Landsat DCPs accepted input from as many as eight environmental sensors in analog, serial digital, or parallel digital form. Eight channels of analog data, 64 serial digital bits, or eight 8-bit parallel digital words could be input to a single DCP. Each analog input required the use of one 8-bit word, and the analog input voltage ranged from 0 to +5 volts direct current. Any combination of analog and parallel digital inputs that resulted in 64 bits could be accepted.

The Landsat DCS was used to relay streamflow and snow-water equivalent information from seven remote sites in central Arizona (Figure 29). Examples of a DCP-equipped streamflow-gaging station and a snow-monitoring site are shown in Figures 31 and 32, respectively. On several occasions, the DCPs relayed near-real time data to the Salt River Project during periods of critical reservoir operations (Reference 4). (See Figure 33.)

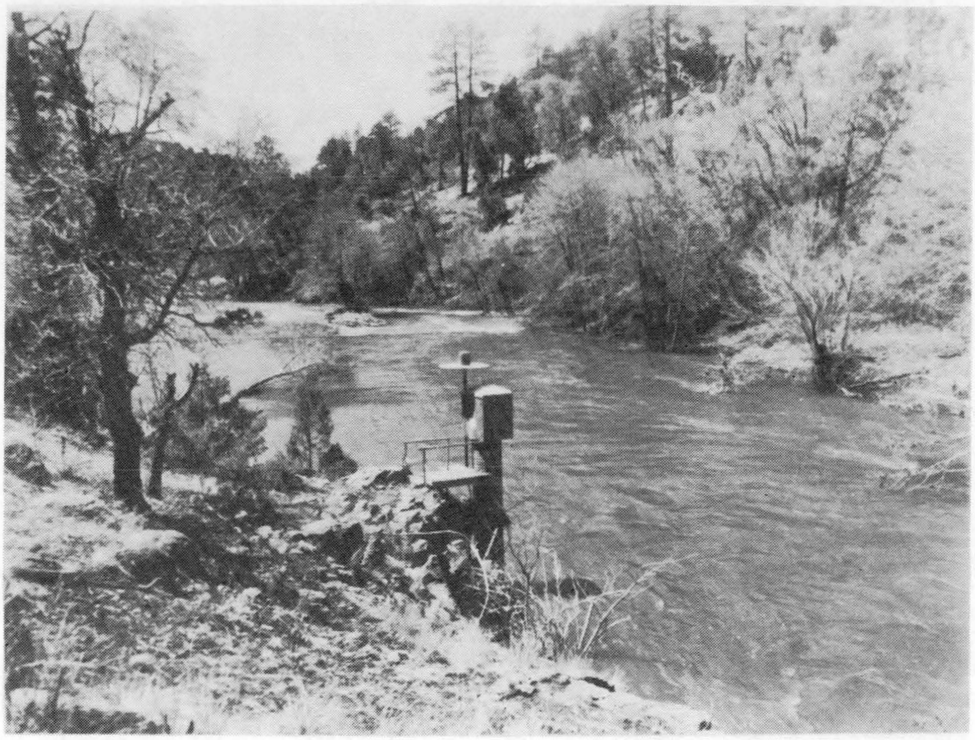

Figure 31. Black River near Point of Pines gaging station equipped with a Landsat data-collection platform.

The Landsat DCPs proved to be reliable under a wide range of environmental conditions and were simple to operate. The main disadvantages of using the Landsat DCS to relay hydrometeorological data were the small amount of information relayed per transmission (64 bits) and the small number of transmissions received each day.

SMS/GOES Data-Collection System

The operational SMS/GOES DCS telemeters large volumes of hydrometeorological data from remote unattended sites at low cost. Data from hydrometeorologic sensors can be transmitted to the SMS/GOES satellites in a self-timed or an

Figure 32. Snow-monitoring site at Baker Butte equipped with a Landsat data-collection platform.

interrogate mode. The SMS/GOES DCPs used in Arizona operate in a self-timed mode—units transmit every 3 hours—and are microprocessor controlled. Data from three streamflow-gaging stations and one snow-monitoring site have been collected at 15-minute intervals and stored in the DCP memory unit (832-bit capacity) for relay every 3 hours to the western satellite (Figure 30). Data from as many as four digital recorders and eight channels of 0 to +5 volt direct current analog data can be processed per update and stored (Reference 20). After each transmission, the DCP is returned to a standby condition for minimum power consumption. When powered by batteries that are recharged by solar panels, the DCPs operate unattended for many months.

Data transmitted by the DCPs are relayed in real time by the SMS/GOES satellites to the NOAA ground-receiving site at Wallops Island, Virginia, and are sent to the World Weather Building near Suitland, Maryland (Figure 30). The data are then relayed to the National Center of the U.S. Geological Survey in Reston, Virginia, where the data are routinely processed into engineering units and sent to Arizona on a weekly basis via a high-speed computer terminal. Unprocessed SMS/GOES DCS data also are available from the NOAA computer center in Suitland, Maryland, in near-real time—less than 1 minute after transmission to the satellite—through the use of low-speed computer terminals. The value of near-real time satellite telemetry was dramatically demonstrated during the storms of March 1978, December 1978, and January 1979 in central Arizona. Streamflow data relayed by the system were used by personnel of the Salt River Project to monitor runoff into the Salt River and to make water-management decisions (Reference 21).

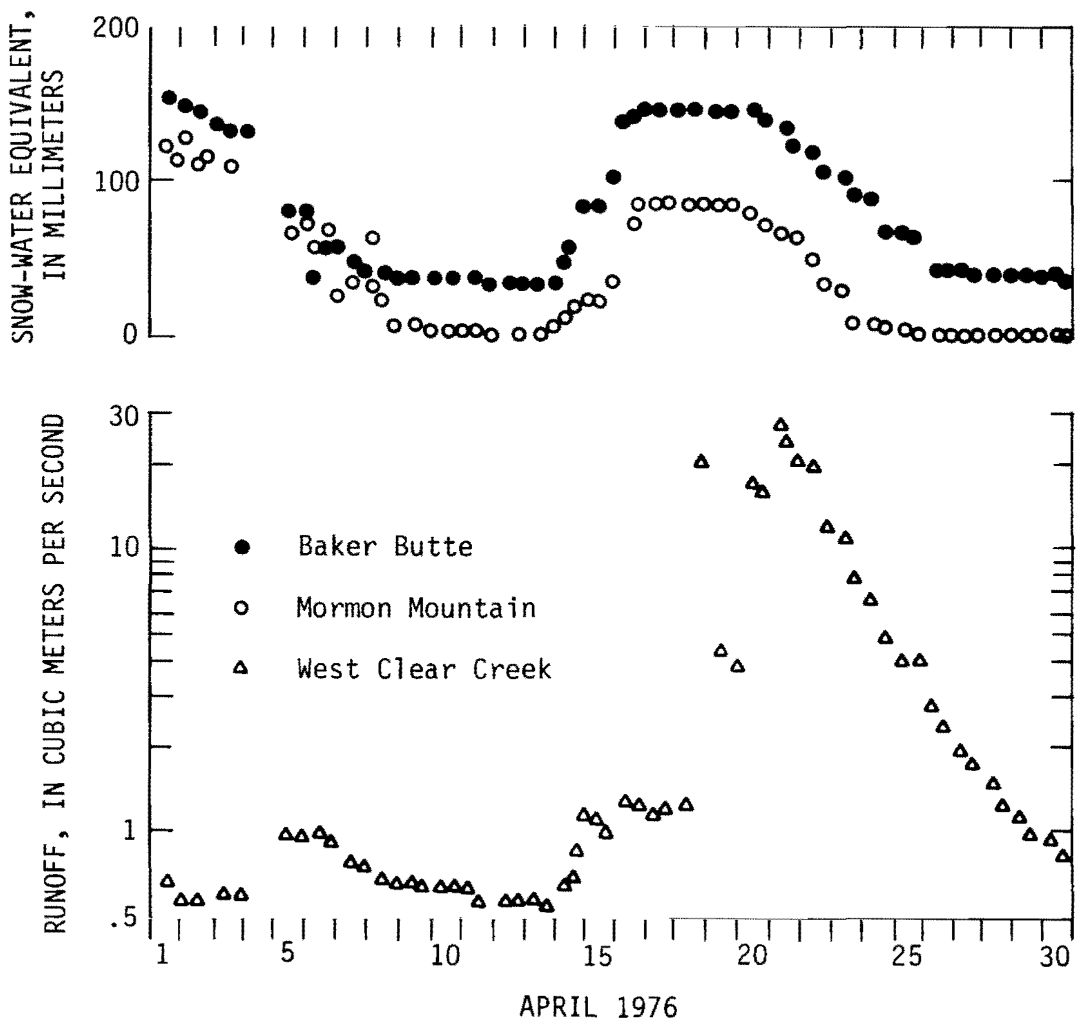

Figure 33. Snow-water equivalents and runoff rates relayed by Landsat data-collection system.

The main advantages of using the SMS/GOES data-collection system to relay hydrometeorological data include the ability to relay large volumes of data from a wide variety of sensors, a high degree of reliability, low equipment and operational costs, and the capability of satellite telemetry in near-real time. The main disadvantages of using the system are the complex operation of microprocessor-controlled data-collection platforms and the fact that the platforms must be activated and operated within precise time windows—within 10 seconds of absolute time.

Snotel System

The Snotel system (Figure 30) implemented by the Soil Conservation Service uses a meteor-burst telemetry technique to relay hydrometeorological data from about 15 snow-monitoring sites in the Salt-Verde watershed (Reference 22). Snow-water equivalents and other data relayed from the sites and snow-covered area measurements from satellite snow-cover observations may permit improved estimates of the volume of water stored in the snowpack.

CONCLUSIONS

The availability of frequent satellite snow-cover observations has greatly reduced the necessity for routine aerial reconnaissance flights over the Salt-Verde watershed. Significant savings have resulted, and the time that flight crews must be exposed to hazardous low-level flights over mountainous terrain has been greatly reduced. Aerial observations, however, will continue to provide valuable information on snow-cover distributions and snow depths during periods of cloud cover that preclude effective satellite snow-cover observations.

Satellite imagery provides the synoptic coverage needed for mapping large snow-covered areas. Although the high-resolution experimental multispectral Landsat imagery permits rapid snow-cover mapping at low cost, only one observation is available every 9 days for a part of the Salt-Verde watershed. In contrast, low-resolution operational imagery acquired by the ITOS and SMS/GOES satellites provides the daily synoptic observations necessary to monitor the rapid changes in snow-covered area in the entire Salt-Verde watershed. However, geometric distortions in meteorological satellite imagery require the use of specialized optical equipment or digital-image processing for snow-cover mapping.

Short-term runoff predictions and information on basin-storage conditions can be made on the basis of snow-cover depletion rates determined from daily satellite observations. Additional research is needed to allow the effective use of snow-covered area measurements in seasonal runoff predictions.

Seasonal runoff predictions have been improved by use of the modified hydrometeorological model in recent years of large runoff volumes. The model also was modified successfully to make short-term runoff predictions.

Hydrometeorological data were successfully relayed by the Landsat and SMS/GOES satellite data-collection systems from remote sites in the Salt-Verde watershed under a wide range of environmental conditions. Hydrometeorological data relayed in near-real time by satellite and conventional telemetry and frequent satellite snow-cover observations were used as an integral part of an early warning system during the floods of spring 1978 and spring 1979.

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16. Abstract The operation of multipurpose reservoirs in central Arizona requires timely and dependable streamflow and snowmelt information. Since 1965, conventional ground surveys and aerial observations have been used in an attempt to monitor rapidly changing moisture conditions in the Salt-Verde watershed. Since 1974, repetitive satellite snow-cover observations have greatly reduced the necessity for routine aerial snow-reconnaissance flights over the mountains. Frequent repetitive coverage is required to monitor rapid changes in snow cover. High-resolution (80-meter) multispectral imagery provided by the Landsat satellite series enabled rapid and accurate mapping of snow-cover distributions for small- to medium-sized subwatersheds; however, the imagery provided only one observation every 9 days of about a third of the watershed. Low-resolution (1-kilometer) imagery acquired by the ITOS and SMS/GOES meteorological satellite series provides the daily synoptic observation necessary to monitor the rapid changes in snow-covered area in the entire watershed. Short-term runoff volumes can be predicted from daily sequential satellite snow-cover observations. Hydrometeorological data relayed in near-real time by satellite and conventional telemetry and satellite snow-cover observations were used as an integral part of an early warning system during the floods of 1978 and 1979.

17. Key Words (Selected by Author(s)) Snow cover, snowmelt-runoff, satellite remote sensing, remote sensing, satellite data collection, telemetry, hydrologic models, satellites-meteorology, runoff-prediction models, Arizona

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