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THE APPLICATION OF ERTS IMAGERY
TO MAPPING SNOW COVER
IN THE WESTERN UNITED STATES

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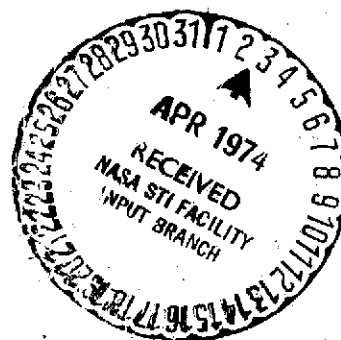
JAMES C. BARNES
CLINTON J. BOWLEY
DAVID A. SIMMES

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16. Abstract

In much of the western United States a large part of the utilized water comes from accumulated mountain snowpacks; thus, accurate measurements of snow distributions are required for input to streamflow prediction models. The application of ERTS imagery for mapping snow has been evaluated for two geographic areas, the Salt-Verde Watershed in central Arizona and the southern Sierra Nevada in California. Techniques have been developed to identify snow and to differentiate between snow and cloud. The snow extent for these two drainage areas has been mapped from the MSS-5 (0.6 - 0.7 µm) imagery and compared with aerial survey snow charts, aircraft photography, and ground-based snow measurements. The results of the investigation indicate that ERTS imagery has substantial practical applications for snow mapping. Snow extent can be mapped from ERTS imagery in more detail than is depicted on aerial survey snow charts. Moreover, in Arizona and southern California cloud obscuration does not appear to be a serious deterrent to the use of satellite data for snow survey. The costs involved in deriving snow maps from ERTS imagery appear to be very reasonable in comparison with existing data collection methods.

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PREFACE

In much of the western United States a large part of the utilized water comes from accumulated mountain snowpacks. The snowmelt runoff is used for irrigation, industrial production, power generation, public consumption, and recreation. Too much runoff may have strong adverse effects in the form of destructive flooding. One only has to look at the 1972-73 winter season to gain an understanding of the impact of snow on the economy of the western part of the country; in central Arizona exceptional winter snowfall resulted in replenished groundwater and a summer of abundant water supplies, whereas in the Pacific Northwest a winter of well-below normal snowfall produced a power-generation crises later in the year.

Observation from earth satellites now offers promise for monitoring snow on a more cost-effective basis than is possible using existing methods. The application of ERTS imagery for this purpose has been evaluated for two geographic areas, the Salt-Verde Watershed in central Arizona and the southern Sierra Nevada in California. In the study, techniques have been developed to identify snow and to differentiate between snow and cloud. The snow extent for these two drainage areas has been mapped from the MSS-5 (0.6-0.7 μm) imagery and compared with aerial survey snow charts, aircraft photography, and ground-based snow measurements.

The results of the investigation indicate that ERTS imagery has substantial practical applications for snow mapping. Snow extent can be mapped from ERTS imagery in more detail than is depicted on aerial survey snow charts. For the areas tested, the agreement between the percentage snow cover as determined from ERTS data and from aerial survey snow charts is of the order of 5% for most cases. Also, although small details in the snow line can be mapped better from higher-resolution aircraft photographs, boundaries of the areas of significant snow cover can be mapped as accurately from the ERTS imagery as from the aircraft photography. Moreover, in Arizona and southern California cloud obscuration does not appear to be a serious deterrent to the use of satellite data for snow survey, and the costs involved in deriving snow maps from ERTS imagery appear to be very reasonable in comparison with existing data collection methods.

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1. INTRODUCTION

1.1 Purpose and Objectives

The purpose of this investigation was to evaluate the application of ERTS-1 data for mapping snow cover, primarily in the mountainous areas of the western United States. The specific objectives were to determine the spectral interval most suitable for snow detection, to determine the accuracy with which snow lines can be mapped in comparison with the accuracies attainable from other types of measurements, and to develop techniques to differentiate reliably between snow and clouds and to understand the effects of terrain and forest cover on snow detection.

The snow extent mapped from the ERTS imagery has been correlated with standard snow measurements, aerial-survey snow charts, and aircraft photography for both mountainous and flat terrain within the United States. The study has been concentrated in two geographic areas: the southern Sierra Nevada in California and the Salt-Verde Watershed in central Arizona. Mountain snow accumulations are of significant hydrologic importance in both of these areas. Data have also been examined for the Upper Columbia Basin in northern Idaho and Western Montana and for the Black Hills area of the Missouri River Basin.

Snow cover is a water resource for which spacecraft observation holds great promise. The results of this study will provide the hydrologist with interpretive techniques that will enable data from future operational satellite systems to be used to map snow on a more cost-effective basis.

1.2 Requirement for Snow Survey Data

The earth's snow cover is a resource that directly or indirectly affects most of the world's population. As written in a report on the needs for polar research (Committee on Polar Research, 1970):

> "Snow forms a transient, sedimentary veneer on much of the earth's land surfaces. The diverse economic effects of this snow layer are incalculable. It is a major and renewable hydrologic reservoir; in many areas of North America more than half of the utilized water is derived from melted winter snow. Flood damage from spring snow melt is a recurring hazard in many river basins. The obstacles and hazards to ground transportation alone are formidable ... ."

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"Snow influences a broad area of geophysical phenomena simply by its presence or absence. On a large scale the winter snow cover stores water, modifies surface albedo, insulates the ground, and modifies plant and animal habitats ... ."

"A large-scale snow cover interacts with large-scale weather phenomena. The sharp increase in surface reflectivity (albedo) which accompanies snow deposition completely alters the radiation regime at the earth's surface. A change in surface albedo and emissivity over widespread areas of the continents modifies both local and large-scale weather patterns ... ."

The economic impact of snow in the western United States was strikingly demonstrated during the 1972-73 winter. In central Arizona exceptional snowfall resulted in replenished groundwater in many areas and a summer of abundant water supplies. In the Pacific Northwest, at the other extreme, a winter of much-below normal snowfall produced a power-generation crisis the following summer.

Although it is difficult to assess in exact dollar amounts the economic value of accurate streamflow forecasting and of snow survey data, estimates have been made for some areas. In a discussion at the Interdisciplinary Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources, held in Monterey, California, in December 1973, it was pointed out that accurate streamflow forecasting is probably worth as much as 40 million dollars a year to the State of California; since snowmelt accounts for a large percentage of the total streamflow, the importance of snow data as input to runoff models is obvious. In the same discussion, it was mentioned that the value of snow survey data in the Pacific Northwest has been determined more directly; the results of a study of three drainage basins showed that the annual benefit from the addition of snow survey data to streamflow forecasting schemes was 385 thousand dollars.

Despite the economic and scientific implications of snow cover, existing data collection methods often cannot provide either the desired areal coverage or observational frequency. Except in limited areas where aerial survey is used, the significant parameters are usually measured at ground stations or at widely scattered snow survey courses. Remote sensing from earth-orbiting satellites now provides observations of snow that have not previously been available and offers promise for eventually providing a more cost-effective means for snowpack monitoring. In fact, as long ago as 1960, snow could be detected in eastern Canada in the initial pictures taken by

the first weather satellite, TIROS-1. Snow, therefore, can perhaps be considered as the very first water resource to be observed from space.

1.3 Application of Satellite Observations to Snow Hydrology

In a report on the management of California's snow-zone lands for water, Anderson (1973) discusses two important characteristics of the Sierra Nevada snowpack: (a) maximum accumulation of snow, and (b) rate of melt of snow water from the pack. The first characteristic is a good indicator of total water yield, and the second of when the resulting water is delivered.

More recently, studies such as those by Leaf (1969) and Leaf and Haeffner (1971) have shown that in mountain snowpacks, a functional characteristic exists between extent of snow cover during the melt season and accumulated runoff. Using aerial photographs, these investigators found that for three drainage basins in the Colorado Rockies the snow-cover depletion relationships are useful for determining both the approximate timing and the magnitude of seasonal snowmelt peaks. Thus, snow extent, which can be readily observed from space, is in itself a significant hydrologic parameter.

Since the time of the first TIROS pictures, an increasing use has been made of remote sensing from satellites to map snow extent. Studies have demonstrated that valuable information on snow distributions could be derived even from the relatively poor resolution data of the earlier meteorological satellites (Barnes and Bowley, 1968 and 1970; McClain, 1970 and 1973). In addition to studies using photographic data, a study of the application of thermal infrared data to snow mapping has also been conducted (Barnes, Bowley and Simmes, 1973). Now, the NOAA and ERTS spacecraft systems are providing data with greatly improved sensor resolutions. The hydrologic applications of the NOAA-2 VHRR (Very High Resolution Radiometer) are discussed by Wiesnet and McGinnis (1973); the preliminary results of snow-mapping studies using ERTS-1 were presented at the Second ERTS Symposium by Barnes and Bowley (1973a) and by Meier (1973).

2. TEST SITES

2.1 Locations of Test Sites

Three geographic areas in the western United States were originally
selected as the primary test sites. The three areas are: (1) the southern
Sierra Nevada in California, (2) the Upper Columbia Basin in northern Idaho
and western Montana, and (3) the Salt-Verde Watershed in central Arizona.
These three areas, each of which has characteristically different terrain,
vegetation, and snowfall climatologies, are all areas in which mountain
snowpacks are of significant hydrologic importance. In addition to the
mountainous terrain areas, the Upper Mississippi-Missouri River Basins
region in the north central part of the country, an area of relatively
flat terrain, was also selected for study. These four test sites are
shown in the map in Figure 2-1.

Because of the mid-summer launch of ERTS-1 the only images displaying
snow cover within the United States during the early weeks of the space-
craft's operation were over the Cascades and Olympic Mountains in the
Pacific Northwest. Imagery for that region was requested, therefore,
for study early in the contract period. As the study progressed, it was
decided to concentrate the effort in two test sites: the southern Sierra
Nevada in California and the Salt-Verde Watershed in Arizona. In these
two geographic areas, favorable cloud conditions permitted a greater
amount of usable ERTS data to be collected. Also, because of the great
hydrologic importance of the snowpacks in these areas, correlative snow
data were more readily available than for the other areas. These two
test sites are described in detail in the following sections.

2.2 Southern Sierra Nevada

2.2.1 Description of Drainage Basins

In the southern Sierra Nevada, the annual streamflow in the areas
adjacent to the southern San Joaquin Valley is the most variable
of any California watershed, due mainly to a large variability in the number
and intensity of the winter storms crossing the region (Anderson, 1963).

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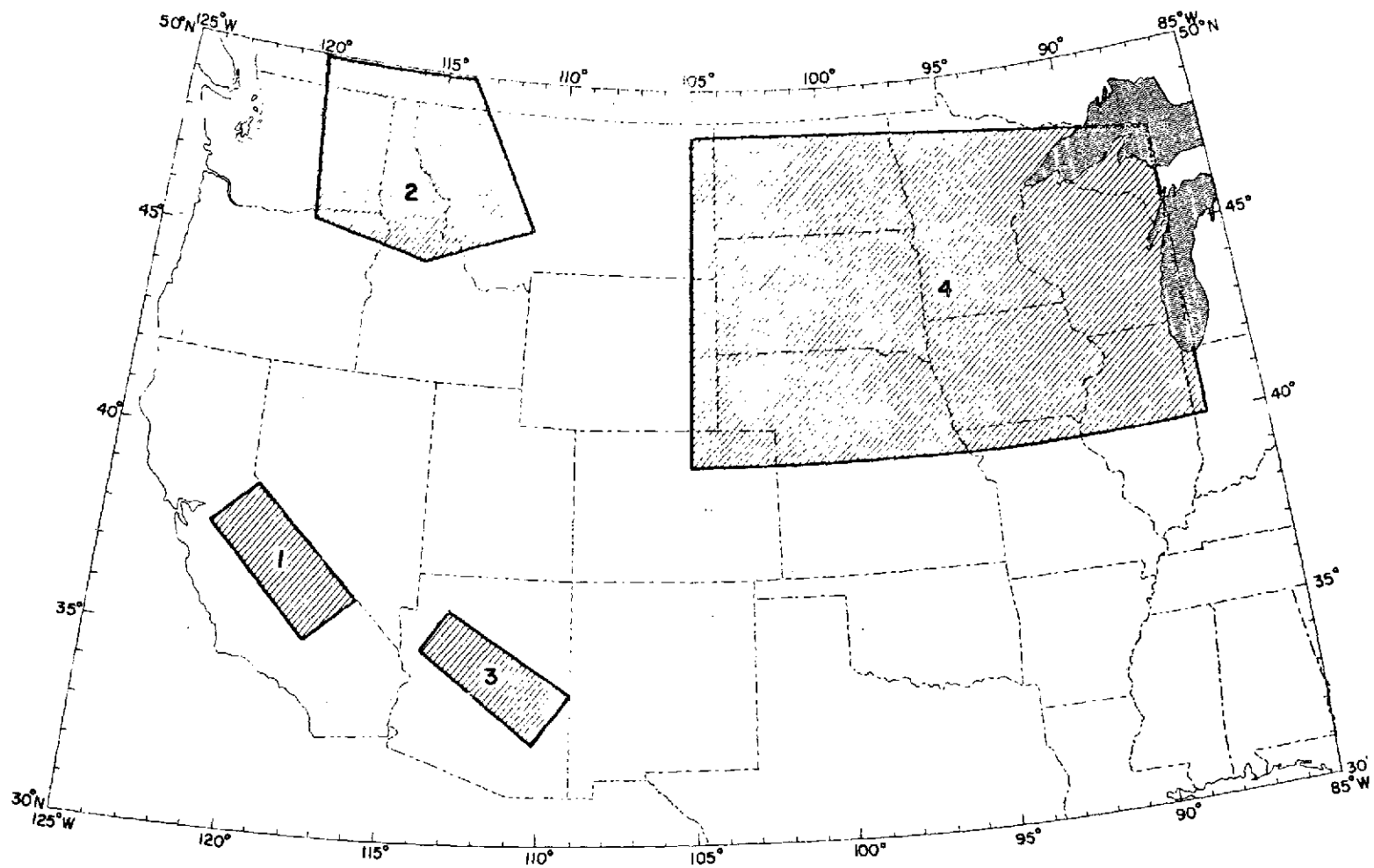
Figure 2-1   Locations of test sites: (1) Southern Sierra Nevada;
(2) Upper Columbia Basin; (3) Salt-Verde Watershed;
(4) Upper Mississippi-Missouri River Basins Region

Moreoever, the results of an earlier study (Barnes and Bowley, 1970) indicated the Sierra Nevada to be a mountainous region for which satellite snow surveillance is particularly promising. Since much of the southern Sierras is not heavily forested, the mountain snowpack can be readily identified in satellite photographs. Cloud-free observations are also plentiful during the spring snowmelt season, generally considered to be from early April through June.

The area of interest in the southern Sierras, shown in Figure 2-2, comprises four river basins, which eventually drain into the San Joaquin Valley. The four basins with their approximate areas are the Kings (4000 km^2), the Kaweah (1450 km^2), the Tule (1013 km^2), and the Kern (5372 km^2); of the total area, therefore, the Kings Basin comprises 34%, the Kaweah 12%, the Tule 9%, and the Kern 45%. As seen in Figure 2-2, the Kings Basin has the highest mean elevation of the four, with approximately half of the basin being above 2500 m; the lowest point is approximately 300 m, at Pine Flat Reservoir. The altitude of the Kern Basin ranges from about 750 m to more than 4000 m; Mt. Whitney, the highest point in the 48 states, is in the Kern Basin. The Kaweah and Tule Basins are both lower in elevation, with the entire Tule Basin lying below 2250 m.

Land usage charts depict the Southern Sierras as consisting primarily of "forest and woodland, mostly ungrazed," with some "forest and woodland, grazed." In a slightly different classification scheme, Anderson (1963) designates the higher elevation as "Alpine" and "Commercial Forest." In this scheme, a narrow band of "Lower Conifer Zone" borders the commercial forest zone along the western slope of the Sierras, with the lower elevation designated as "Woodland-Brush-Grass Zone." Despite the apparent abundance of forest-covered land, Court (1963) points out that in total area the Kings River Basin is only 28% forested; furthermore, trees are so sparse in the forested area that only about 17% of the basin is covered by the tree canopy. For the Sierras as a whole, Court reports that 76% of the area is exposed to the sky.

2.2.2 Snowpack Conditions During 1972-73 Season

In the southern Sierras, the snowpack was above normal for the sample period, the 1972-1973 snow season. The California Department of Water

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1500

Lake Tahoe
2250
3000
2250
Mono Lake
2250
3000
1500

Kings
Kaweah
Tule
Kern

7977

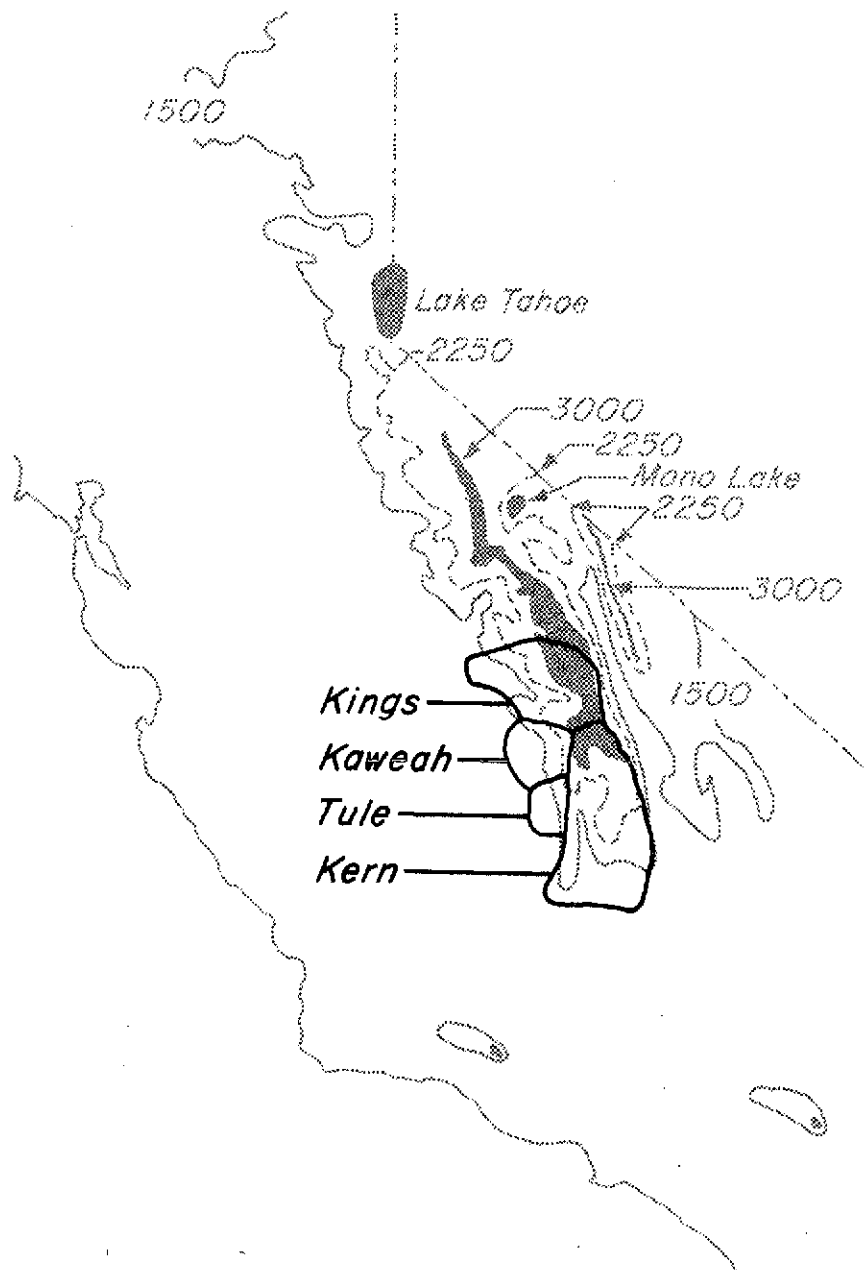Figure 2-2   Map showing river basins in southern Sierra Nevada test site.
Elevation contours are in meters

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Resources reports that early in the winter the snowpack that had accumulated by late December was depleted at lower elevations and reduced at higher elevations by warm storms during early January, but subsequent storms and colder weather brought the snowpack to above normal by the first of February. A relatively wet February raised the water content of the snowpack, and the continuation through March of cool, wet weather boosted the snow water content to greater amounts in most watersheds. On the first of April, the snow water content at mid-elevations of the Kern, Kaweah, Tule, and Kings River Basins was greater in percentage of normal than at the higher elevations. In fact, two snow courses in this area had water contents that exceeded the maximum water content ever recorded. Although precipitation was below normal during April, the snowpack water content was still well above normal in early May. Snow course measurements made about the first of May indicated a snowpack water content as high as 315% of average in the Tule River Basin. On this date the water-year streamflow for the San Joaquin drainage area was forecast to be 100% to 150% of average.

2.3 Salt-Verde Watershed

2.3.1 Description of Drainage Basins

In a paper discussing the use of remote sensing as a water management tool on the Salt-Verde Watershed, Warskow (1971) points out that all of the irrigation projects in central Arizona rely on runoff from the winter snowpack as their major source of surface water; for example, 56 years of runoff record show that 68% of the 1,138,362 acre feet mean annual runoff from the Salt-Verde watershed comes from snowmelt during the January to May runoff period. Although the water content of the Salt-Verde snowpack is diminutive in comparison with that of areas such as the Sierras and Cascades, it is still the major source of surface runoff in the State of Arizona. The Arizona snowpack is extremely variable from year to year because of its location at the southern edge of the continental snowpack, and rapid snowmelt can occur at lower elevation areas at anytime during the snow season.

The Salt and Verde River Basins are considerably larger in area than the individual basins of the southern Sierras, being 15,128 km^2 and 14,646 km^2, respectively. The boundaries of the watershed are shown in the map
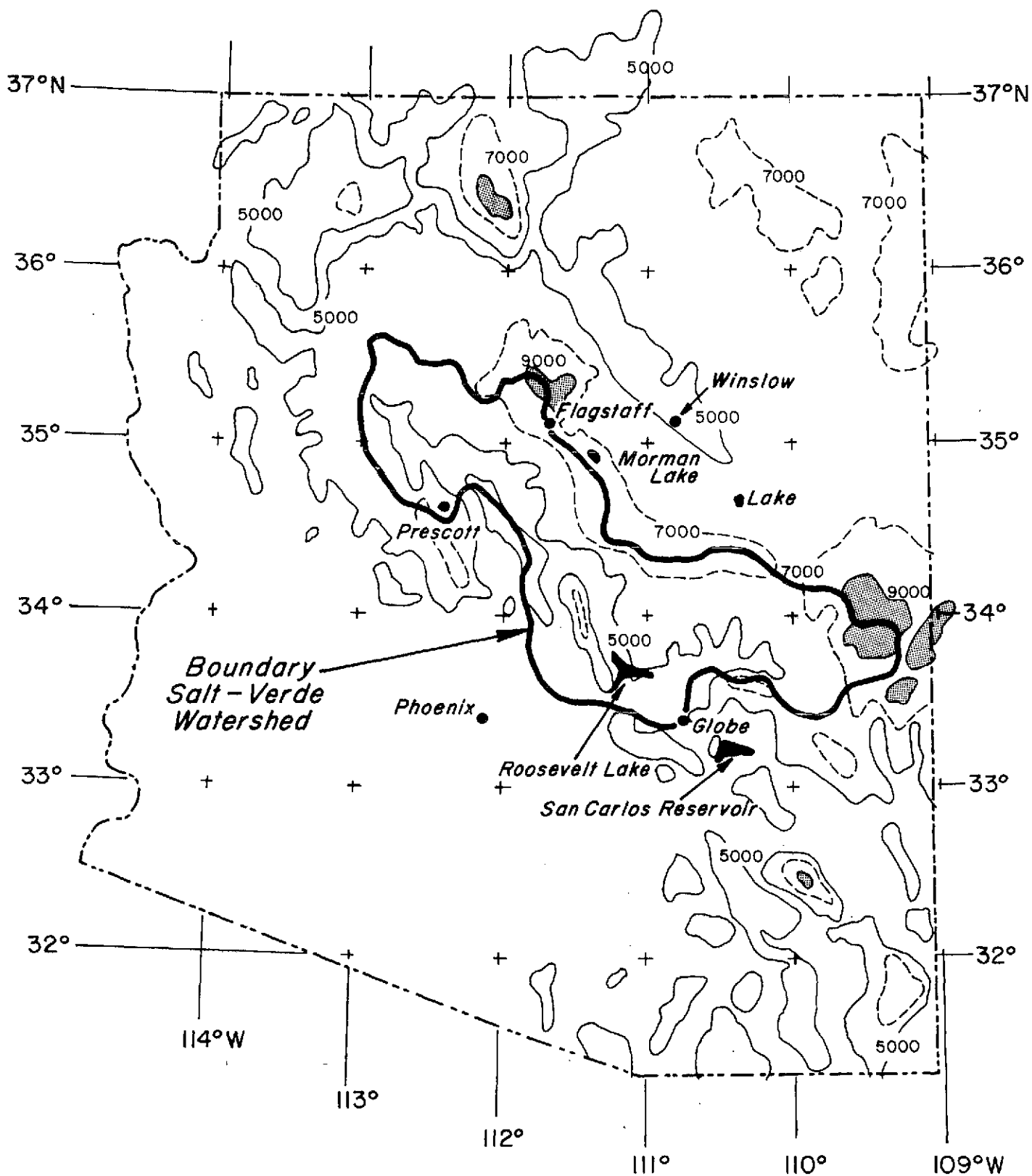
Figure 2-3   Map showing Salt-Verde Watershed test site. Contours for
1500 m (5000 ft), 2100 m (7000 ft), and 2700 m (9000 ft)
are indicated.

in Figure 2-3. The Salt Watershed ranges in elevation from 390m to 3480m, and the Verde from 400m to 3780m. The majority of the Salt River flow is derived from runoff in the White Mountains area at the eastern end of the watershed.

The Salt-Verde Watershed is indicated on land-usage charts to consist of "forest and woodland, grazed" or "open woodland, grazed," and thus is less forested than the southern Sierras. The predominant growth in the forested areas is Ponderosa Pine; other areas consist of Juniper zones and grasslands.

2.3.2 Snowpack Conditions During 1972-73 Season

As pointed out above, the Arizona snowpack is extremely variable from year to year; for example, in 1968 the pack was measured in feet, whereas in 1971 it was measured in inches and fractions of inches (Warskow, 1971). In 1972-73, a near-record snowpack accumulated in the Salt-Verde Watershed. Precipitation for the October through April period was much above normal, and the snowpack at its maximum in early April was estimated to be as much as 500% of normal in the Verde River Watershed and 300% in the Salt. At one location, a snow depth of 132 inches with a water content of 52 inches was measured; normally, the maximum water content is about 10 inches. The April issue of Water Supply Outlook (published by the National Weather Service) gives a runoff forecast for the Verde of nearly 400% of the 1953-67 average and for the Salt of more than 350%. Obviously, throughout the 1972-73 winter-spring season, snow hydrology was a vital concern in Arizona water management programs.

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3. DATA SAMPLE

3.1 ERTS-1 Data

ERTS-1 was placed into a near-polar, sun-synchronous orbit at a height of 900 km on 23 July 1972. Except for a brief period in early August 1972, the MSS (Multi-Spectral Scanner) sensor system has operated continuously, returning approximately 188 data scenes each day, 44 of which are over the United States. The MSS views a swath 180 km wide, with coverage of the exact same area occurring every 18 days. Some orbital overlap occurs on two consecutive days. Studies of the MSS data, as reported at the various ERTS-1 symposia, have indicated that features greater than about 70 m in width can be identified and can be mapped accurately to a scale of at least 1:250,000. The MSS senses in four spectral bands: MSS-4 (0.5-0.6 μm), MSS-5 (0.6-0.7 μm), MSS-6 (0.7-0.8 μm), and MSS-7 (0.8-1.1 μm).

The ERTS-1 data obtained for use in this investigation were in the imagery format. Both 70 mm negative transparencies and 9.5 inch positive paper prints were received from the NASA Data Processing Facility (NDPF) through the standing order procedure. Through the retrospective request procedure, data covering the Cascades were received for a limited time period during the late summer and fall of 1972. A sample of color composite data in the 9.5 inch positive transparency format was also obtained for the southern Sierra Nevada, the Salt-Verde Watershed, and the Black Hills area of South Dakota.

The initial images received for analysis were for the Cascades area in late July and early September 1972. Thereafter, data were received for all test sites for the entire winter-spring season of 1972-73. The amount of data received for each test site was, of course, dependent on cloud conditions. A sizeable data sample was collected, however, for the southern Sierras test site during the period from 16 September to 30 June; similarly, a considerable amount of usable data was collected for the Salt-Verde Watershed test site during the period from 21 November to 2 May. Cloud observations severely limited the amount of useable data for the Upper Columbia Basin site.

3.2 Correlative Snow Data

Standard snow depth reports given in the climatological data summaries by state (available from the National Climatic Center), snow course measurements from sources such as the California Cooperative Snow Survey program published by the State of California Department of Water Resources, and aerial survey snow charts available from the Army Corps of Engineers and the Salt River Project Office were used as correlative snow data for the test sites in the western mountains. Of these data sources the aerial survey snow charts were found to be the most useful; the climatological data summaries do not provide many observations in mountainous areas, and the snow course measurements are only taken in certain areas at monthly intervals during the late winter and spring. Snow depth charts for the Black Hills area were obtained from the Kansas City River Forecast Office; other information, such as area-elevation curves for the river basins of interest, was obtained from River Forecast Offices in Sacramento and Portland.

Aerial snow surveys are flown over the Salt-Verde Watershed at approximately two-week intervals throughout the snow season. During periods of critical snowmelt flights are made more frequently. From the aerial observation, an ocular estimate is made of the snow depth using the logs left from timber operations in the mountain areas, ground and vegetation textural characteristics and cultural features (such as fences, road cuts) as indicators of the snow depth (Warskow, 1971); both the aerial outline of the snowpack and the observed depths are recorded on a map overlay.

The Sacramento Office of the Corps of Engineers compiles aerial survey snow charts for the four-basin southern Sierras area at two-week intervals, normally beginning about the first of April and continuing through the snowmelt season. Five flights were made in 1973, the first being on 27 April and the last on 11 June (the start of the aerial survey program was delayed until late April because of an accident involving the aircraft while on a photography mission earlier in the winter; although, fortunately, no serious injuries occurred to the occupants, this incident does point up a hazard associated with aerial observing programs over rugged, mountainous terrain). The charts compiled

from the aerial surveys indicate only snow extent and provide no snow depth estimates.

Because of the much below normal snowfall, only three limited aerial surveys were conducted over the Upper Columbia Basin during 1973 by the Seattle Office of the Corps of Engineers. The procedure used in that region is to give the snow line elevation in various drainage basins rather than to map the snow extent.

3.3 Aircraft Photography

In support of the ERTS program, aircraft photography was taken for the southern Sierras and central Arizona test sites by the NASA/ARC Earth Resources Aircraft Project. The high-altitude aircraft data consist of 70 mm black and white photography (plus X2402 film in the 0.475-0.575 μm and 0.580-0.680 μm spectral bands, and infrared aerographic -2424 film in the 0.690-0.760 μm band), 70 mm color photography (aerochrome infrared -2443 film in the 0.510-0.900 μm spectral band), and 9-inch color photography (same film as above). The 70 mm photography is from a Vinten camera with a 1.75-inch focal length, and the 9-inch photography is from an RC-10 camera with 6-inch focal length.

The flight over the southern Sierra Nevada was on 20 February. Parts of two of the flight segments were within the four-basin test site, and a third segment was just northeast of that area crossing Mono Lake and the Owens River Valley near Bishop. The flight over the central Arizona mountains was made 16 March. Two flight segments intersected portions of the test site; one segment crossed the Flagstaff area at the northern tip of the Verde Watershed, whereas the other crossed the Mt. Baldy area in the easternmost part of the Salt Watershed.

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4. DATA ANALYSIS PROCEDURES

4.1 Processing of Imagery

In general, the quality of the ERTS data products received from the NDPF was very good. Some of the 9.5-inch prints did appear to be either too light or too dark, however, with considerable variation in the overall density from pass to pass over the same test site. The 70 mm negatives received early in the study period were of a density that made their use difficult with standard photographic processing equipment; this difficulty was corrected in the later negatives. In some of the positive prints received from the NDPF later in the study period, the darkest features are surrounded by an area of much brighter tone. For example, this "halo" effect is pronounced in some prints showing the Mono Lake area in California. Since the halos are not apparent in the 70 mm negatives, new prints were prepared for the images in question. It is presumed that the halo effect is due to the "dodged print" processing announced in the ERTS Investigators Bulletin of 10 April 1973.

Both the original 9.5-inch prints supplied by the NDPF and reprocessed enlarged prints were used in the data analysis. The scale of the 9.5 inch prints is 1:1 million, and the scale of the enlarged prints, which were processed from the 70 mm negatives at ERT's photography laboratory, is 1:500,000. For most of the analysis procedures, the enlarged prints were found to be the most useful to work with. Patterns could be analyzed more easily at this scale; furthermore, the aerial survey snow charts for the southern Sierras are at a scale of 1:500,000, so that transfer of the information from the ERTS image to the aerial survey base map could be easily accomplished. For the Salt-Verde Watershed, the aerial survey snow charts were at a scale of 1:1 million; therefore, the 1:1 million scale prints were used for most of the analysis of that test site. As discussed in the following section, experimentation with the exposure time when processing the enlarged prints also resulted in a product in which certain snow patterns could be mapped more accurately.

4.2 Procedures for Identifying and Mapping Snow

4.2.1 Most Useful Spectral Band for Detecting Snow

In the two ERTS spectral bands that are in the visible range, snow
can be identified because of its high reflectance in comparison to that
of areas not snow covered. Examination of the initial images containing
snow cover revealed that the contrast between snow-covered and snow-free
terrain is greatest in the MSS-5 (0.6-0.7 µm) spectral band. Although
snow is also readily identified in the MSS-4 (0.5-0.6 µm) band, the
contrast between snow and no snow overall is somewhat less than in the
MSS-5 data. Moreover, at higher sun angles snow-covered areas are near
saturation in the MSS-4 band, causing a loss of some detail in the snow
patterns. Therefore, snow extent has been mapped using primarily the
MSS-5 imagery.

Although snow can be detected in the longer wavelength bands, the
contrast between snow-covered and snow-free terrain is considerably
lower than in the visible bands. The lower contrast is particularly
evident in the MSS-7 near-IR band (0.8-1.1 µm). Because of the reduced
contrast, the MSS-7 imagery is not as useful for mapping snow extent;
however, as discussed in Section 8.1 of this report, the near-IR data
may provide useful information for detecting melting snow surfaces.
Other investigations, also discussed in Section 8.1, have shown the
near-IR data to be extremely useful for identifying sea ice types and
determining certain characteristics of glaciers.

4.2.2 Procedures for Distinguishing Between Snow and Clouds

In the ERTS-1 visible spectral bands, snow cover and clouds both
have high reflectances. Mountain snow cover can be distinguished from
clouds, however, through the following interpretive keys:

● Pattern Recognition. Mountain snowpacks cover the higher ele-
vation terrain and, thus, are directly related to the geologic structure.
Since the configuration of the geologic structure of typical mountain
ranges is quite different from the patterns of clouds as viewed from
space, the snow cover can be instantly recognized. Additionally, in an

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area of relatively steep terrain, such as the eastern slope of the Sierras, the snow line is usually well-defined and forms a sharper boundary than is characteristic of most cloud edges.

● Recognition of Terrestrial Features. Terrestrial features can be recognized in cloud-free areas. Because of the high-resolution of the ERTS imagery, numerous terrestrial features that are not visible in lower resolution meteorological satellite photographs can be recognized. In addition to natural features, such man-made features as roads, power line swaths, and cultivated fields are detectable; in the heavily forested areas of the Cascades, timber cuts are clearly visible. In non-mountainous regions, such as the Midwest, recognition of terrestrial features is the most reliable method to distinguish snow from clouds.

○ Uniformity of Reflectance. Snow cover in areas that are not forested typically has a more uniform reflectance than do clouds. Furthermore, the distinct changes in reflectance that are associated with forested and nonforested areas are not found in cloud patterns. In the color composite data the snow cover also appears "whiter" than do most clouds.

● Shadows. Cloud shadows can often be detected, particularly with cumuliform clouds. Detection of cloud shadows on the underlying terrain is an important interpretive key during the spring season when cumuliform clouds tend to develop over mountain ranges. At times of low sun angle, north slopes of mountain ridges may also be in shadow; these shadows, however, can be distinguished from cloud shadows because they fit the configuration of the geological structure.

● Pattern Stability. In the area of overlap between ERTS passes on successive days, bright patterns that remain stable can be identified as snow cover, since cloud patterns seldom remain stable for more than a few hours. This interpretive key is particularly useful for identifying snow and ice features at higher latitudes where a greater overlapping of ERTS passes occurs.

4.2.3 Mapping Techniques

In the analysis procedure the snow line was mapped at the edge of the brighter tone without regard to changes in brightness within the overall area deduced to be snow covered. Although snow-covered areas often exhibit fairly uniform reflectance, variations due primarily to forest effects are observed. For the specified test sites the snow limit was mapped from the 9.5-inch ERTS prints supplied by NASA (scale: 1:1 million) and, in some instances, from reprocessed enlarged prints (scale: 1:500,000). As discussed above, the scale of available correlative snow charts determined in part the scale selected for analysis. The snow patterns mapped from the images on transparent overlays were transferred to appropriate base maps for correlation with ground-truth data. The areal extent of the snow cover in the various drainage basins was measured using a planimeter.

4.3 Measurement of Snow Line Elevation

One method used to measure the snow line elevation was to overlay the snow pattern mapped from the ERTS image directly onto an elevation contour chart. In this method, reference was made to charts from the National Topographic Map Series (scale: 1:250,000). Although the scale of these charts is larger than that of the ERTS prints, charts of this scale were found to be the most useful for matching the amount of detail in the ERTS data. In the procedure used, grid lines, corrected where necessary, were first drawn on each overlay at 15-minute latitude-longitude intervals. Similarly, elevation contours at 300 m (1000 feet) intervals were drawn on overlays at the scale of the topographic charts. The snow limit mapped from the ERTS data was then transferred to the contour overlay using the configuration of the pattern as a guide in adjusting the scale. The final adjustment was made using a variable-scale rule to check the corresponding distances of selected features at the two scales.

The snow line elevation determined from a direct comparison with a contour chart, however, was found to vary considerably even within a particular drainage basin. For example, the Kings River Basin in the southern Sierras was divided into three sections, and the mean elevation for each section was determined from a large number of data points. For three cases during the spring season, the mean difference between the

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section with the highest snow line elevation and that with the lowest is 420 m. As a check, to determine whether the difference might be due to ERTS mapping inaccuracies, a similar procedure was followed with the three aerial survey snow charts for approximately the same dates. The mean difference for these charts is 480 m, somewhat greater than was found for the ERTS data. For both the ERTS and aerial survey data the differences are fairly consistent; in each instance the snow line elevation is highest in the eastern part of the basin, along the Middle and South Forks of the Kings River.

The snow line elevation determined directly as described above was then compared with the snow line elevation determined by measuring the percentage of the basin snow covered and referring to the area-altitude curve for the particular basin. In an earlier study using meteorological satellite photography, the snow line elevation for the Kings Basin was determined in this way (Barnes and Bowley, 1970). With regard to ERTS data, the snow line determined from the areal snow extent, the "equivalent snow line altitude," has been discussed further in a paper by Meier (1973). When referring in this report to the snow line elevation measured with reference to the area-elevation relationship, the term "ESA" (Equivalent Snow Line Altitude) suggested by Meier will be used.

In the Kings Basin, the mean absolute difference between the measured snow line and the ESA for nine cases is 100 m. In five cases the ESA is higher than the measured elevation, and in four cases it is lower; the maximum difference is 267 m on 27 November, the ESA being higher than the measured elevation. In all cases tested, the ESA is between the maximum and minimum values measured directly through comparison with elevation contours. In the Kaweah Basin, the mean difference between the ESA and measured snow line is nearly 150 m, with the ESA being lower in seven of the nine cases; similarly, in the Tule Basin the difference is about 150 m, with the ESA being lower in six of the nine cases. In the Kern Basin, the difference is 50 m for three cases tested.

Because of the observed variation in the snow line elevation measured directly, which can be influenced significantly by small mapping errors, it is believed that the equivalent snow line altitude (ESA) is a more meaningful measurement with regard to the application of satellite data to snow mapping.

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4.4 Mountain Shadow Effects

During the mid-winter period, low sun angles produce mountain shadows that can cause ambiguity in locating the snow line. The reflectance of a north-facing ridge that is partially or totally snow covered may appear the same as the reflectance of terrain that is completely free of snow. This problem is more serious, of course, in the northern parts of the country. Of the two test sites in California and Arizona, the problem was found to be more serious in the Sierra Nevada because of the numerous ridges and canyons in that mountain range.

In an effort to resolve the mountain shadow problem, the snow line elevation in the Kings Basin in the southern Sierras for four cases (21 October, 27 November, 2 January, and 20 January) was mapped both from the original 9.5-inch prints and from reprocessed enlarged prints. The enlarged prints, which are at a scale of 1:500,000, were processed from the 70 mm negatives using various exposure times in order to bring out more detail in the dark shadow areas.

A comparison of the prints revealed that in many instances the shadow effects are reduced through the reprocessing. In some areas, in fact, snow-no snow boundaries that were obscured in the original prints can be detected. This is particularly evident in the 2 January case; the original ERTS print for that date is shown in Figure 4-1, and the reprocessed print in Figure 4-2. Because of the apparent better snow definition, the reprocessed en-larged prints were used for the Sierras test site.
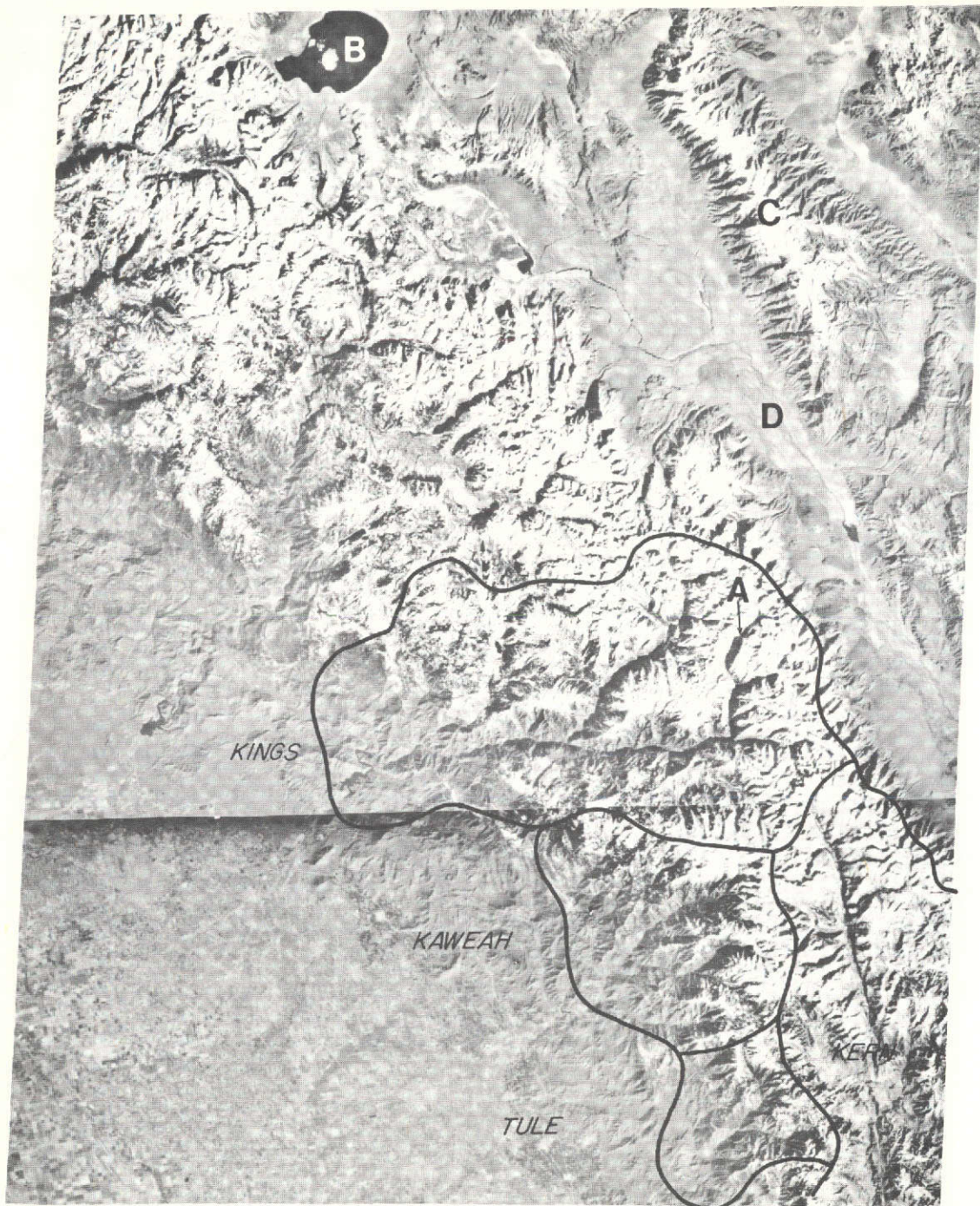
Figure 4-1   ERTS-1 MSS-5 imagery (ID Nos. 1163-18063 and -18065) showing
southern Sierra Nevada, 2 January 1973. The boundaries of
the River Basins are indicated. Within the Kings Basin, north-
facing slopes (such as at A) are in shadow. Other features
include Mono Lake (B), White Mountains (C), and Owens Valley (D).

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Figure 4-2   Reprocessed enlargement of the Kings River Basin area of the image shown in Figure 4-1. The shadow effect at A is reduced through the reprocessing. The snow line in the Kings Basin is indicated.

5. RESULTS OF DATA ANALYSIS:
SOUTHERN SIERRA NEVADA TEST SITE
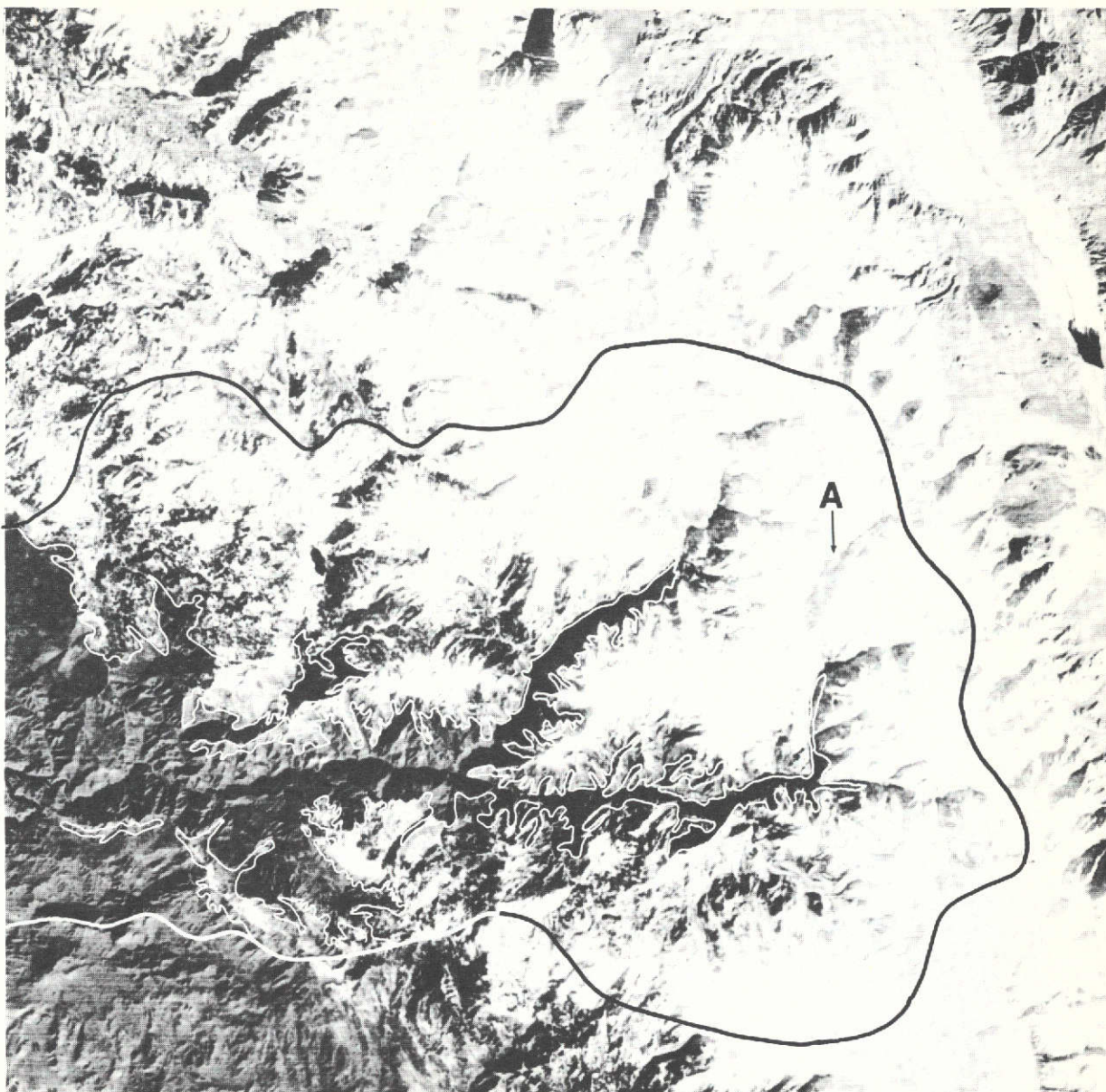
5.1 ERTS Coverage

The entire four-basin area of the southern Sierra Nevada test site is not covered in a single ERTS pass. In the ERTS orbital configuration, the southeastern part of the area, including the Kern, Tule, and Kaweah Basins and part of the Kings Basin, is covered on one day; on the following day the coverage again includes the Tule and Kaweah Basins and the entire Kings Basin. In the late spring, however, when the snow extent is limited, it is possible to map the total snow extent within the test site from a single ERTS pass.

The useable ERTS data sample is given in Table 5-1. Although the entire test site could not be mapped on each ERTS repeat cycle because of cloud obscuration, a considerable amount of cloud-free coverage was available. In fact, in only three instances was the entire area cloud covered on both ERTS passes. In the Kings Basin the snow extent could be mapped on eleven of the sixteen repeat cycles from September through June, and, more importantly, on seven of the eight cycles during the late winter and spring snowmelt season from late February through the end of June.

ERTS images showing the snow cover distribution in the southern Sierras during the fall season are given in Figures 5-1 through 5-3; the dates of these data are 16 September, 21 October, and 27 November 1972. An example of mid-winter snow conditions (20 January 1973), with the snow line at a low elevation, is given in Figure 5-4. Two ERTS images during the spring snow-melt season, on 20 April and 26 May 1973, are given in Figures 5-5 and 5-6. Other ERTS data for the southern Sierra Nevada test site are discussed in later sections of the report.

5.2 Snow Line Elevation Measurements

The initial analysis of the data sample acquired during the fall season demonstrated that dynamic changes in snow line elevation could be mapped from ERTS. An area in illustration is the White Mountains, the range just east of the Sierras with peaks from 3,600 to 4,260 meters high. On 16 September (Figure 5-1), it is difficult to detect any snow in the White Mountains; only at

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TABLE 5-1

ERTS DATA SAMPLE FOR SOUTHERN SIERRA NEVADA TEST SITE

| Date of ERTS Pass	Useful Data Acquired for River Basin			
	Kings	Kaweah	Tule	Kern
15-16 September 1973	X	X	X	
21-22 October 1972		X	X	X
8-9 November 1972				
26-27 November 1972	X	X		X
14-15 December 1972				X
1-2 January 1973	X	X	X	
19-20 January 1973	X	X	X	
6-7 February 1973				
24-25 February 1973	X	X	X	
14-15 March 1973	X	X	X	X
1-2 April 1973				
19-20 April 1973	X			
7-8 May 1973	X	X	X	X
25-26 May 1973	X	X	X	
12 June 1973	X	X	X	X
30 June 1973	X	X	X	X
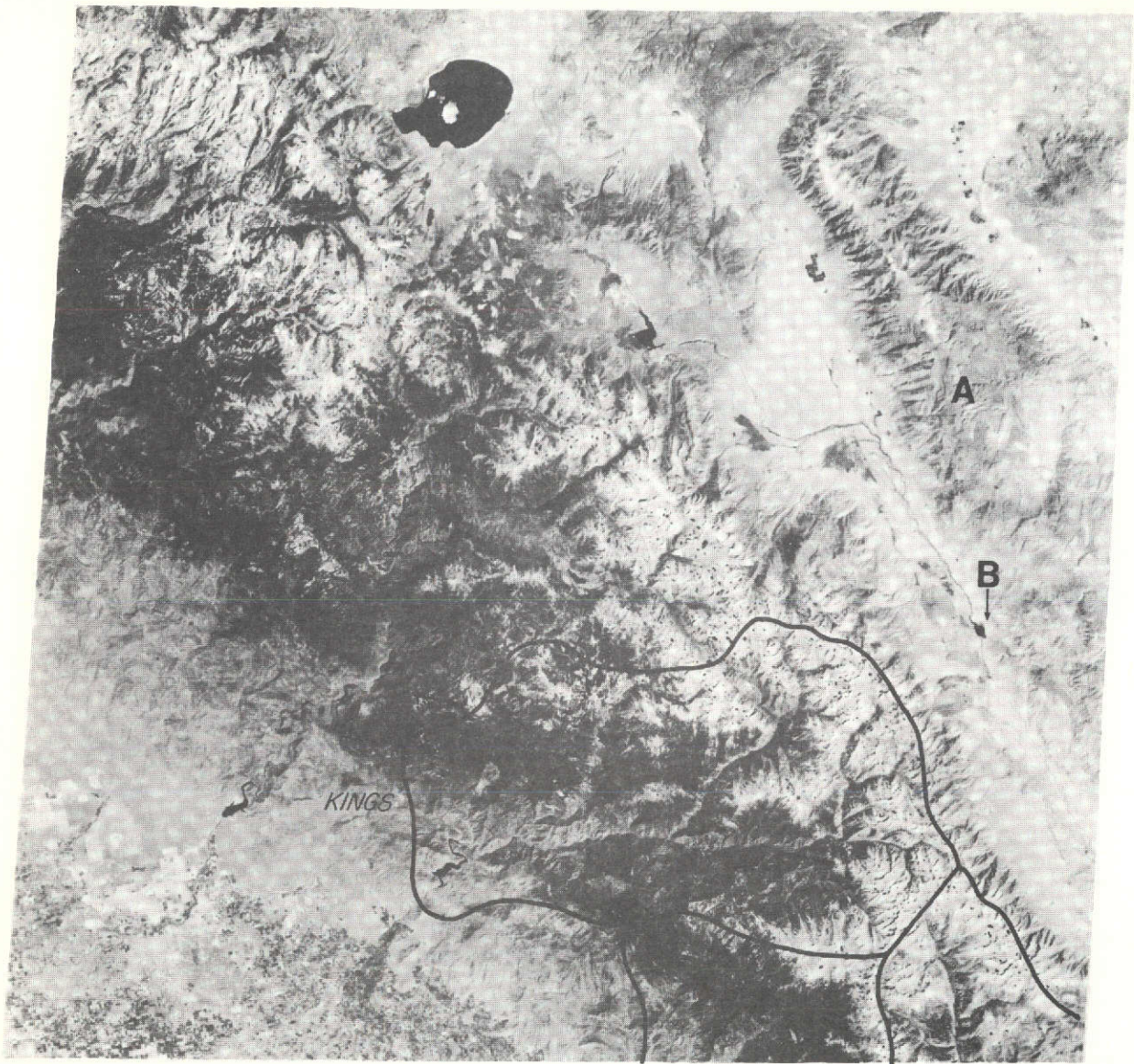
Figure 5-1   ERTS-1 MSS-5 image (ID No. 1055-18055) showing southern Sierra
Nevada, 16 September 1972. The Kings Basin is indicated; White
Mountains (A) and Tinemaha Reservoir (B) are also indicated.
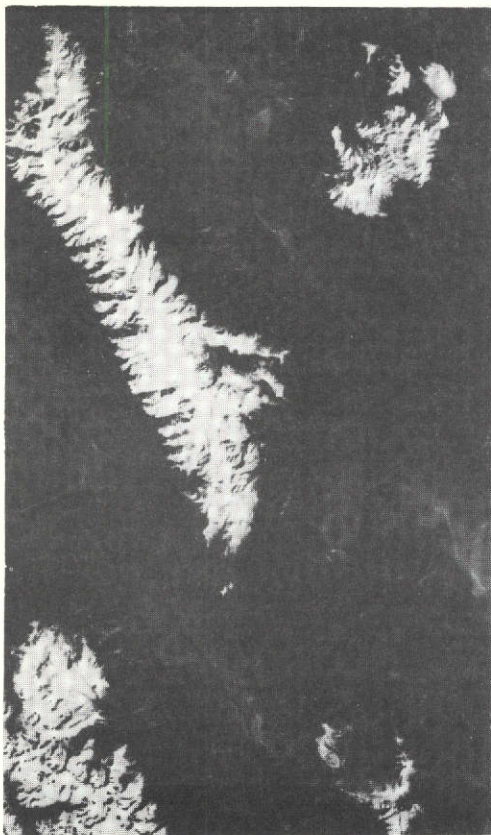
Figure 5-2   Portion of ERTS-1 MSS-5 image
             (ID No. 1090-18003), 21 October
             1972. Note increased snow cover
             in White Mountains as compared
             to Figure 5-1

Figure 5-3   Portion of ERTS-1 MSS-5 image
             (ID No. 1127-18064), 27 November
             1972. Note decreased snow cover
             in White Mountains as compared
             to Figure 5-2; Tinemaha Reservoir
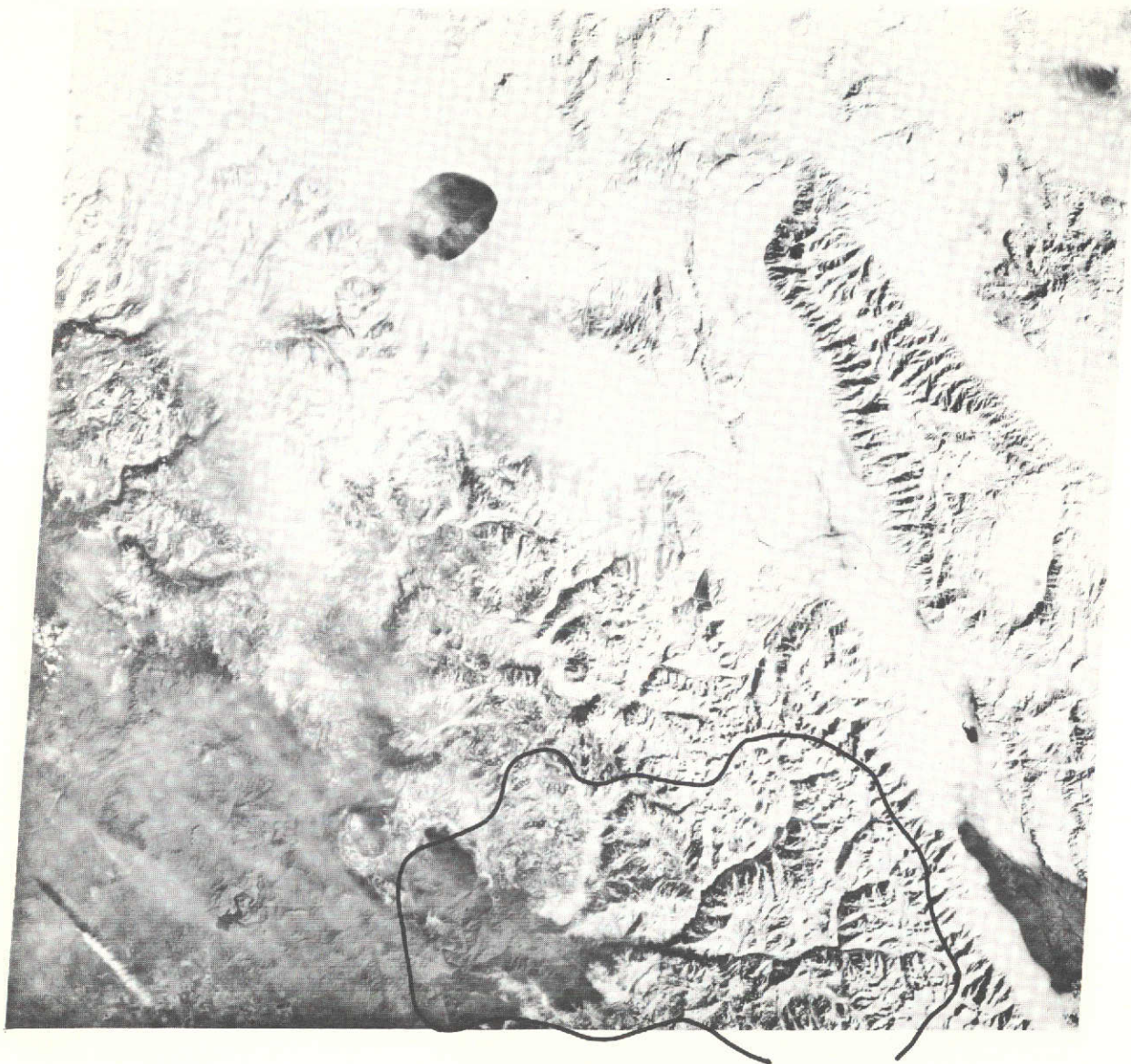   is at lower right corner

Figure 5-4   ERTS-1 MSS-5 Image (ID No. 1181-18062) showing Southern Sierra
Nevada, 20 January 1972. Note increase in extent of snow cover
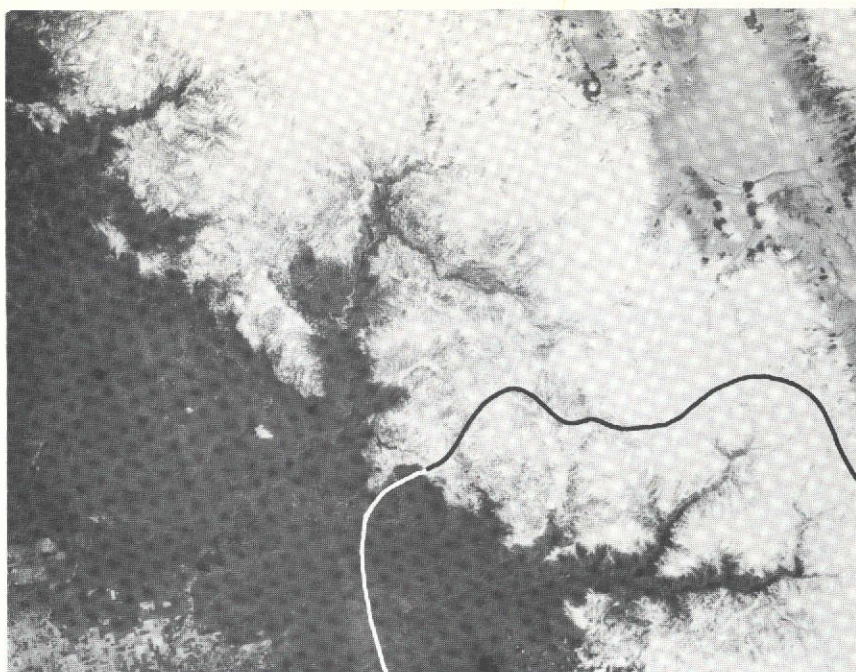as compared to Figure 4-1. Kings River Basin is indicated.

Figure 5-5   ERTS-1 MSS-5 Image (ID. No. 1271-18070) showing Kings River
              Basin, 20 April 1973. Boundary of basin is indicated.

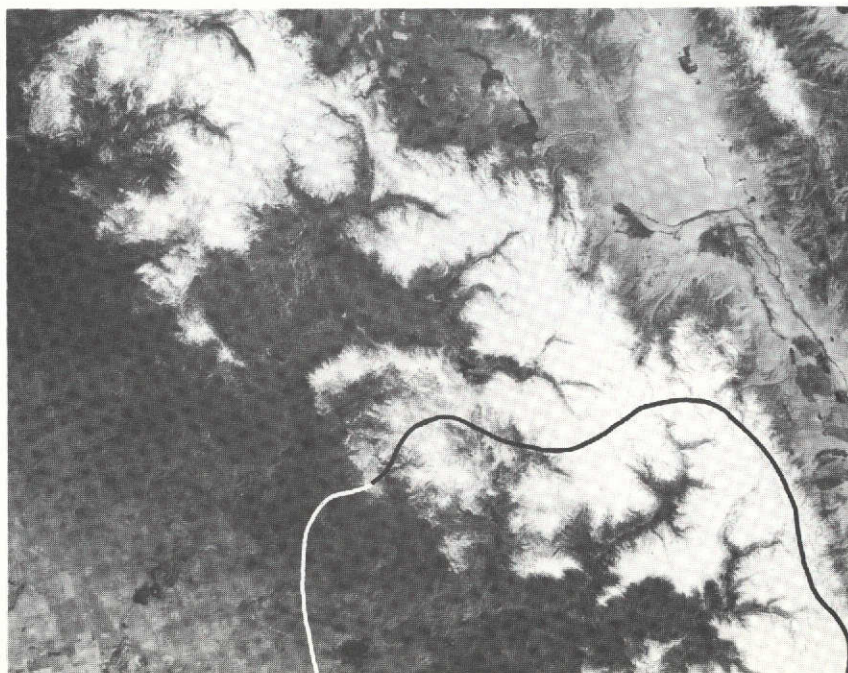
Figure 5-6   ERTS-1 MSS-5 Image (ID No. 1307-18064) showing same area as in
              Figure 5-5, 26 May 1973. Note decrease in snow cover during the
              36-day interval.

the highest elevations above about 3,800 meters does it appear that any snow cover exists. Five weeks later on 21 October (Figure 5-2), a dramatic lowering of the snow line has occurred; the snow line elevation has dropped to 2,100 meters (mean of 25 points) along the western slope, and to 3,150 meters (mean of 30 points) along the eastern slope. Meteorological data indicate that more than 20 inches of snow fell at a station at the 3,750 meter level on the three days immediately preceding the ERTS observation.

The ERTS image on 27 November (Figure 5-3) shows, however, that significant snowmelt has apparently occurred during the next five-week period. The snowmelt is particularly evident along the western slope, where the snow line has receded some 1,200 meters to an elevation of 3,300 meters (mean of 33 points). Of interest also is that the ERTS data show that during the period from 16 September to 27 November, the Tinemaha Reservoir, located west and just south of the White Mountains in the Owens Valley, increases significantly in size. On the earlier date, the reservoir measures 2.8km north to south, whereas in late November, the length of the reservoir has increased to about 3.7km.

Graphs displaying the equivalent snow line altitude (ESA) by date for each of the four river basins in the test site are given in Figures 5-7 and 5-8. The ESA was measured by the method described in Section 4.3. The salient features of the graphs are discussed in the following paragraphs.

No definitive snow line was mapped from the 16 September imagery (Figure 5-1). On that date the highly reflective area that might be interpreted as snow coincides almost exactly with the higher elevation area indicated on the topographic maps to be non-forested. Personnel in California involved in snow measuring activities are in general agreement that continuous snow cover would be unlikely during September, even at the highest Sierras elevations. It is most likely, therefore, that the area of high reflectance includes bare rock as well as some remaining snow fields.

A comparison with later data (for example, the 21 October image in Figure 5-2) shows that areas of continuous snow cover have a higher reflectance than any part of the 16 September image. Also, even in the late spring (Figures 5-5 and 5-6), the snow line is distinct, even though being at a high elevation; no distinct snow line is evident in Figure 5-1. As discussed in Section 8 of the report, analysis of the multispectral ERTS data further clarifies the interpretation that continuous snow cover does not exist in the September observation.

The lowest elevation snow line was measured on 20 January, the ESA being approximately 1,000 meters in the Kaweah and Tule River Basins on that date. The snow line on 20 January is significantly lower than that measured on 2 January. The change in snow extent during the eighteen day interval is readily apparent by comparing the ERTS image on the 20th (Figure 5-4) with the image on the 2nd (discussed in Section 4.4); on the 20th, snow cover exists in much of the Owens Valley just east of the Sierras. Meteorological data indicate that a major snowfall period occurred in the Sierras from 16 to 19 January, with substantial snowfall reported at stations as low as the 1,200 meter level; stations in the San Joaquin drainage received most of their January precipitation during this period.

The graphs shown in Figures 5-7 and 5-8 indicate a substantially higher snow line elevation a month later for the three river basins observed. In the ERTS imagery for 25 February, which is discussed in Section 5.4, it can be seen that the snow extent has decreased as compared with 20 January; the decrease is particularly evident in the lower Owens Valley, where the snow cover seen in the late January imagery has completely disappeared.

Despite the lesser snow extent, some mid-elevation stations are reporting a somewhat greater snowpack in February than on 20 January. In contrast to the January weather regime, however, no significant snowfall occurred during the period preceding the 25 February observation (no snow fell from the 16th through the 23rd; very light amounts were reported at some stations on the 24th). It is reasonable, therefore, that much of the snow that had fallen at low elevations in January had disappeared by late February.

The Kaweah and Tule Basins were observed on both 14 and 15 March in the overlapping areas of the two ERTS images. The ESA for the two basins is significantly different for the two days, however, being some 300 meters higher on the 15th. The difference is too great to be attributed to an analysis error, and, in fact, a careful check of the respective images reveals an apparent real difference in snow extent. Weather records provide a possible explanation for the apparent difference. A period of precipitation occurred on the 11th through the 13th, ending with a frontal passage early on the 14th (Grant Grove, a station in the Kaweah Basin at a 2,000 meter elevation reported 9 inches of snowfall on 14 March). It is probable, therefore, that in the morning of the 14th at the time of the ERTS observation, the freshly fallen snow is still on the tree canopy; a day later much of the
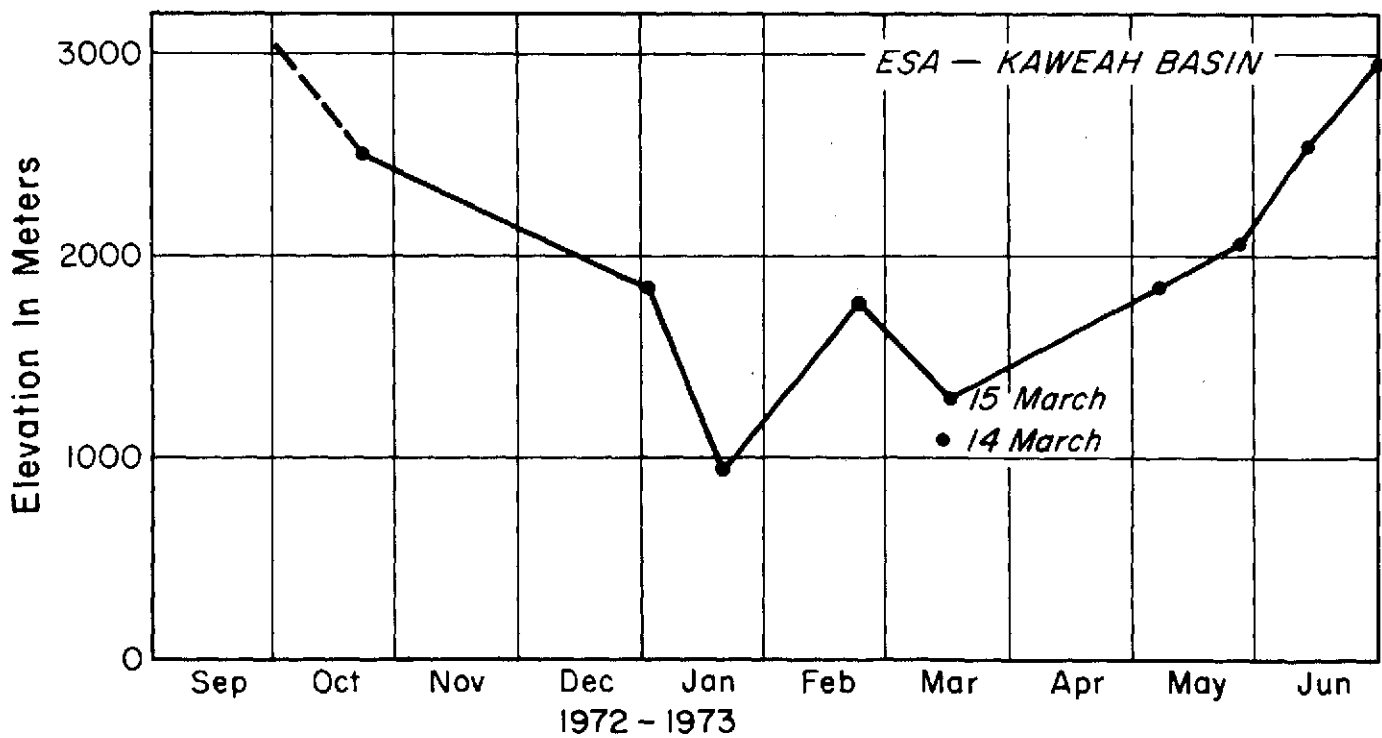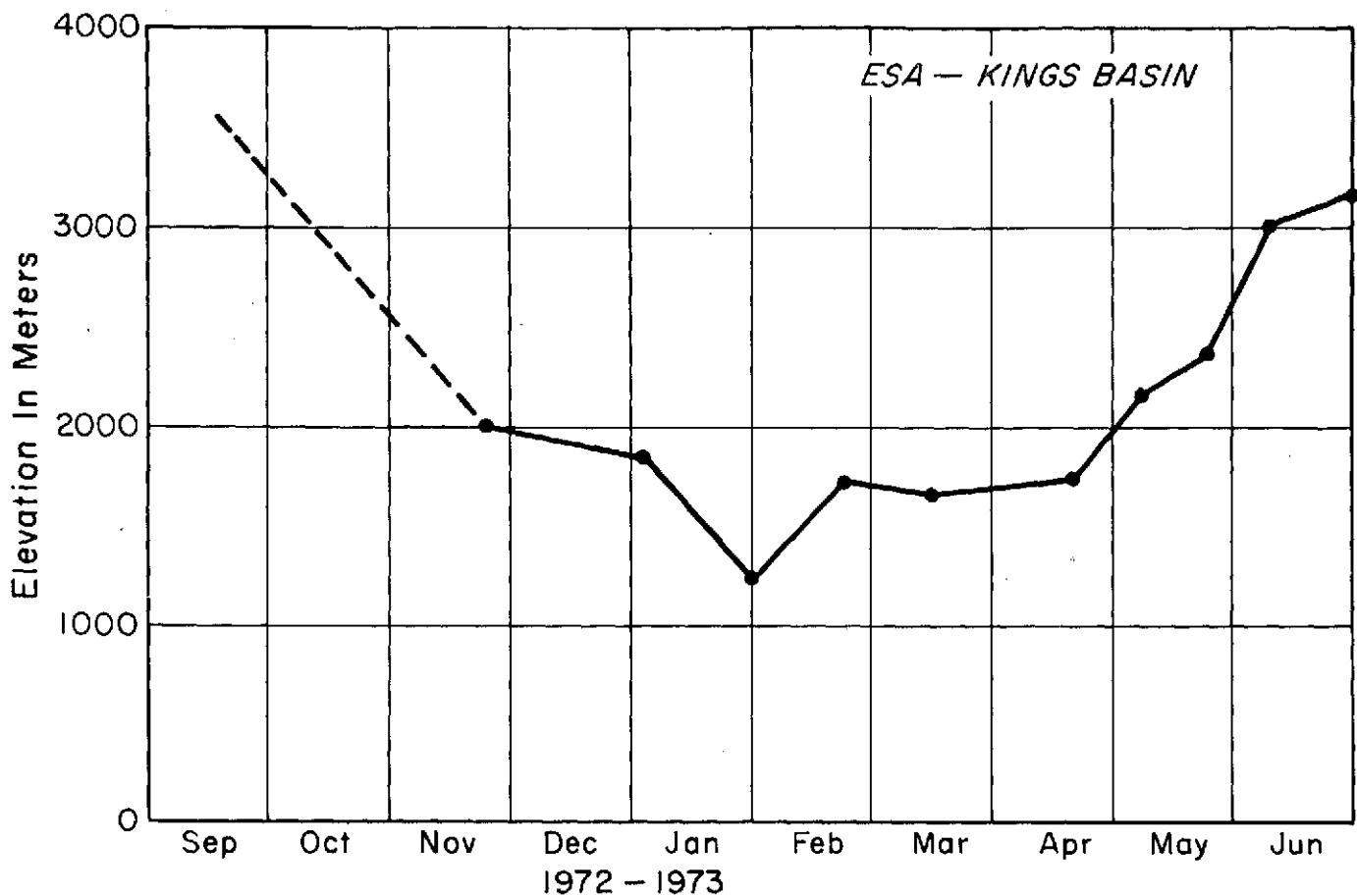
32

Figure 5-7   ESA (Equivalent Snow line Altitude) computed from ERTS data for Kings and Kaweah Basins. ESA was not computed for 16 September observation.
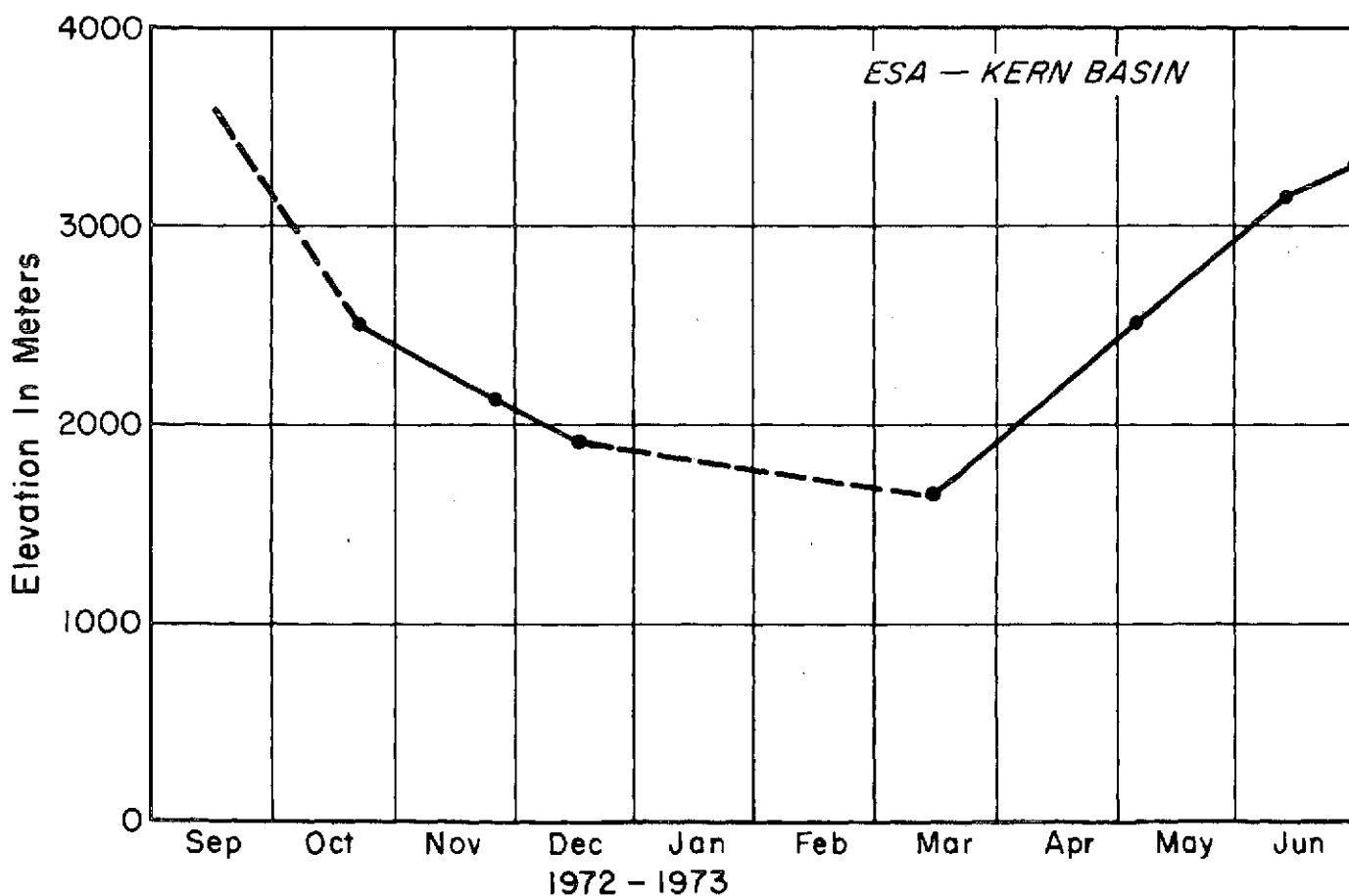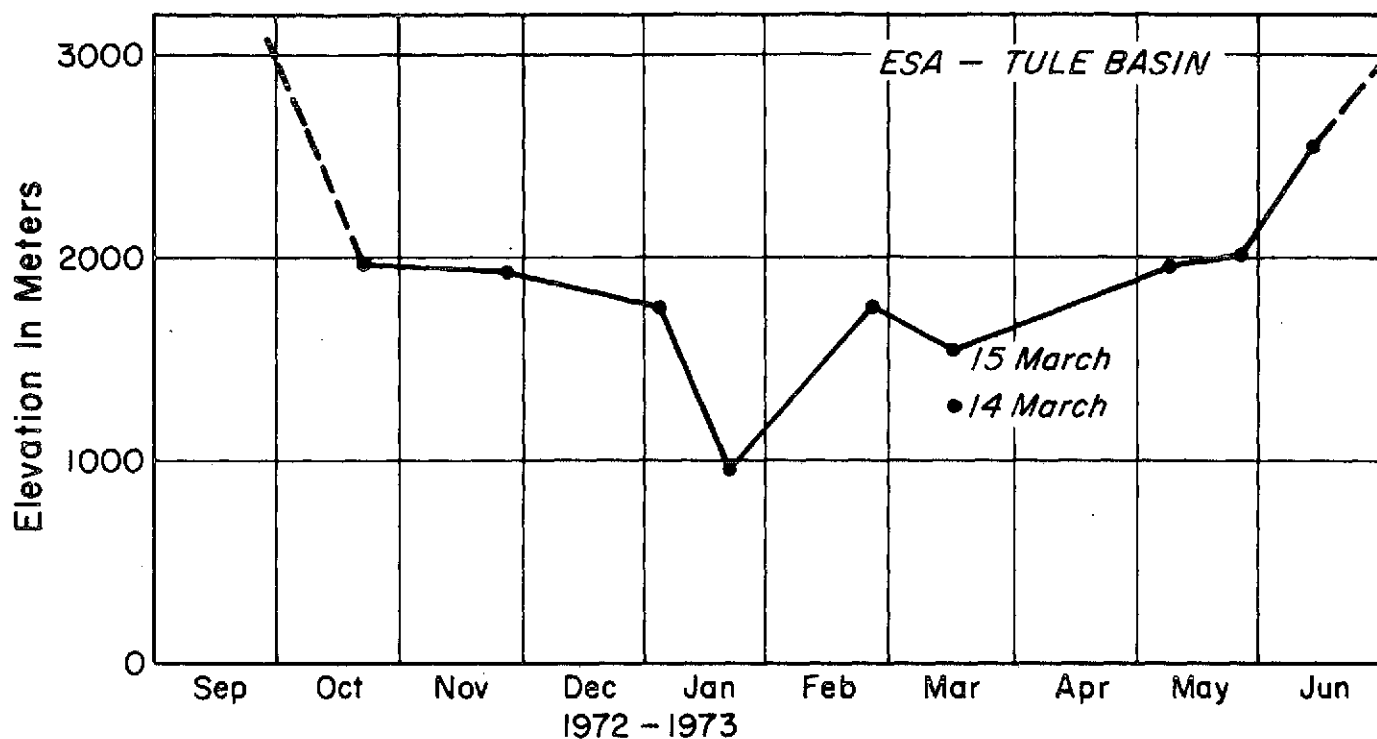
Figure 5-8   ESA (Equivalent Snow line Altitude) computed from ERTS data for
Tule and Kern Basins.   ESA was not computed for 16 September
observation, nor for the Tule Basin on 30 June; cloud-free
imagery was not available for the Kern Basin between 14 December
and 14 March.   34

snow would have fallen off the trees, lowering the surface reflectance. Thus, the snow extent on the 15th is probably the better indication of the boundary of the significant snowpack.

Later in the spring, a steady retreat in the snow line elevation is observed. The decrease in snow extent in the Kings Basin during the interval between 20 April and 26 May is clearly evident in the images shown in Figures 5-5 and 5-6. By the end of June, snow remains only at the high elevations of the southern Sierras (the 30 June data are discussed in Section 8.1).

5.3 Comparison Between ERTS Data and Aerial Survey Snow Charts

Aerial survey snow charts depicting the snow extent in the four river basins of the southern Sierras were prepared by the Corps of Engineers on five dates between 27 April and 11 June. Maps comparing the snow extent as mapped from ERTS imagery and as depicted on the aerial survey charts for the four instances when the two observations were only a few days apart are given in Figures 5-9 through 5-12. From an examination of the comparative snow extent maps, it appears that more detail in the snow line can be mapped from the ERTS imagery than is mapped by the aerial observer. This is a reversal from the results of studies using lower resolution meteorological satellite data (Barnes and Bowley, 1970), in which the snow line mapped from space was smoother than the snow line mapped by the aerial observer.

The percentage of snow cover within each river basin was computed from each ERTS image and each aerial survey snow chart using a planimeter. The percentages are plotted in Figure 5-13, and the differences between the ERTS and aerial survey values for the four cases shown in the comparative charts are tabulated in Table 5-2; this table also gives the differences in the ESA values derived from ERTS and from the aerial survey charts.

The results of the comparison indicate overall close agreement between the ERTS and aerial survey data. For each case tested the percentage of the basin snow covered measured from ERTS is somewhat greater than that measured from the aerial survey. Thus, the ESA determined from ERTS is lower than the ESA determined from the aerial survey chart. The maximum difference in percentage snow cover is 6% for every basin tested except one; the one value greater that 6% is 14% for the Kaweah Basin in the comparison between the 26 May ERTS and 22 May aerial survey observations.

Figure 5-9   Comparative map for southern Sierra Nevada test site showing
               snow line mapped from ERTS imagery on 20 April and depicted on
               aerial survey chart for 27 April.

Figure 5-10 Comparative map for southern Sierra Nevada test site showing snow line mapped from ERTS imagery on 7-8 May and depicted on aerial survey chart for 11 May.
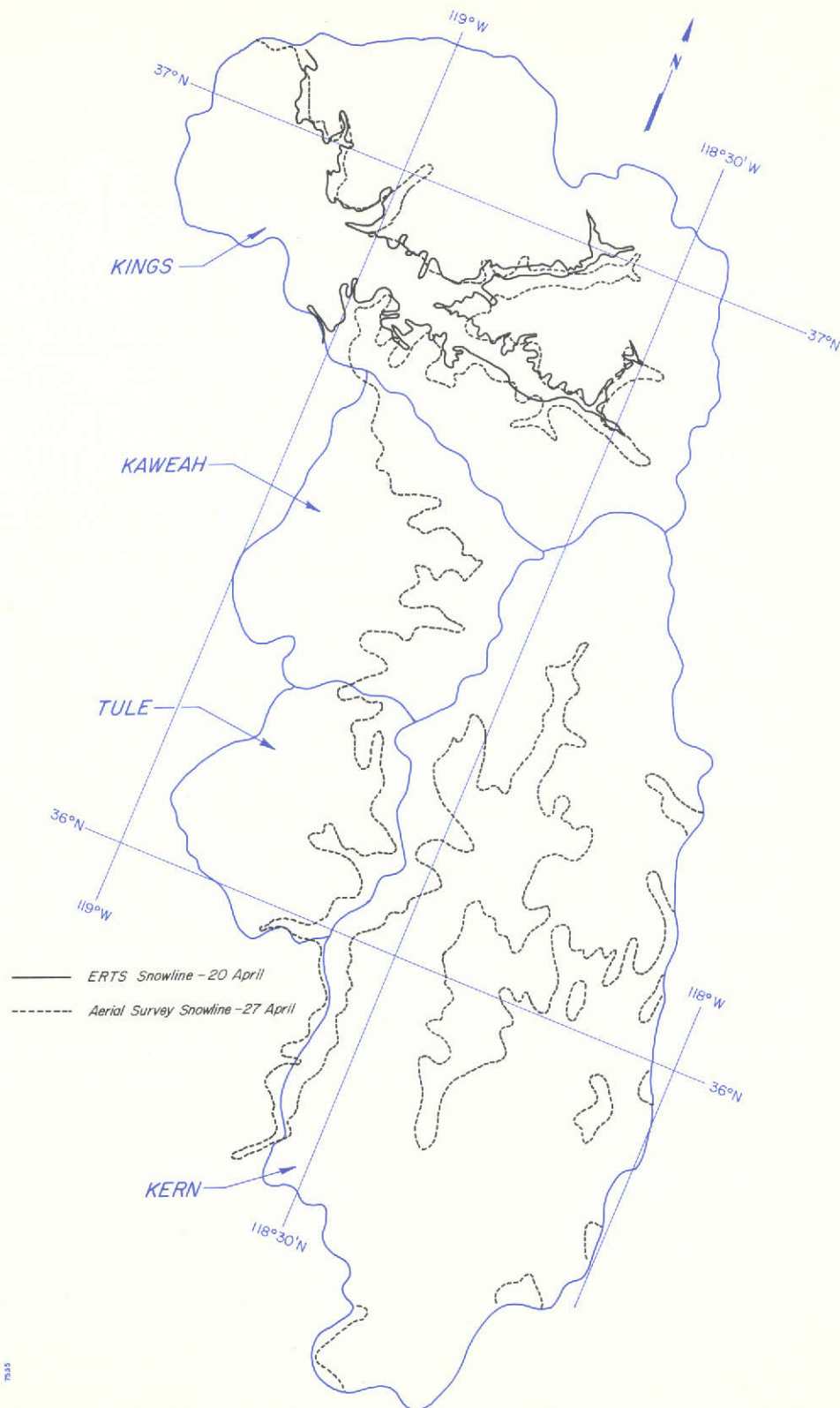
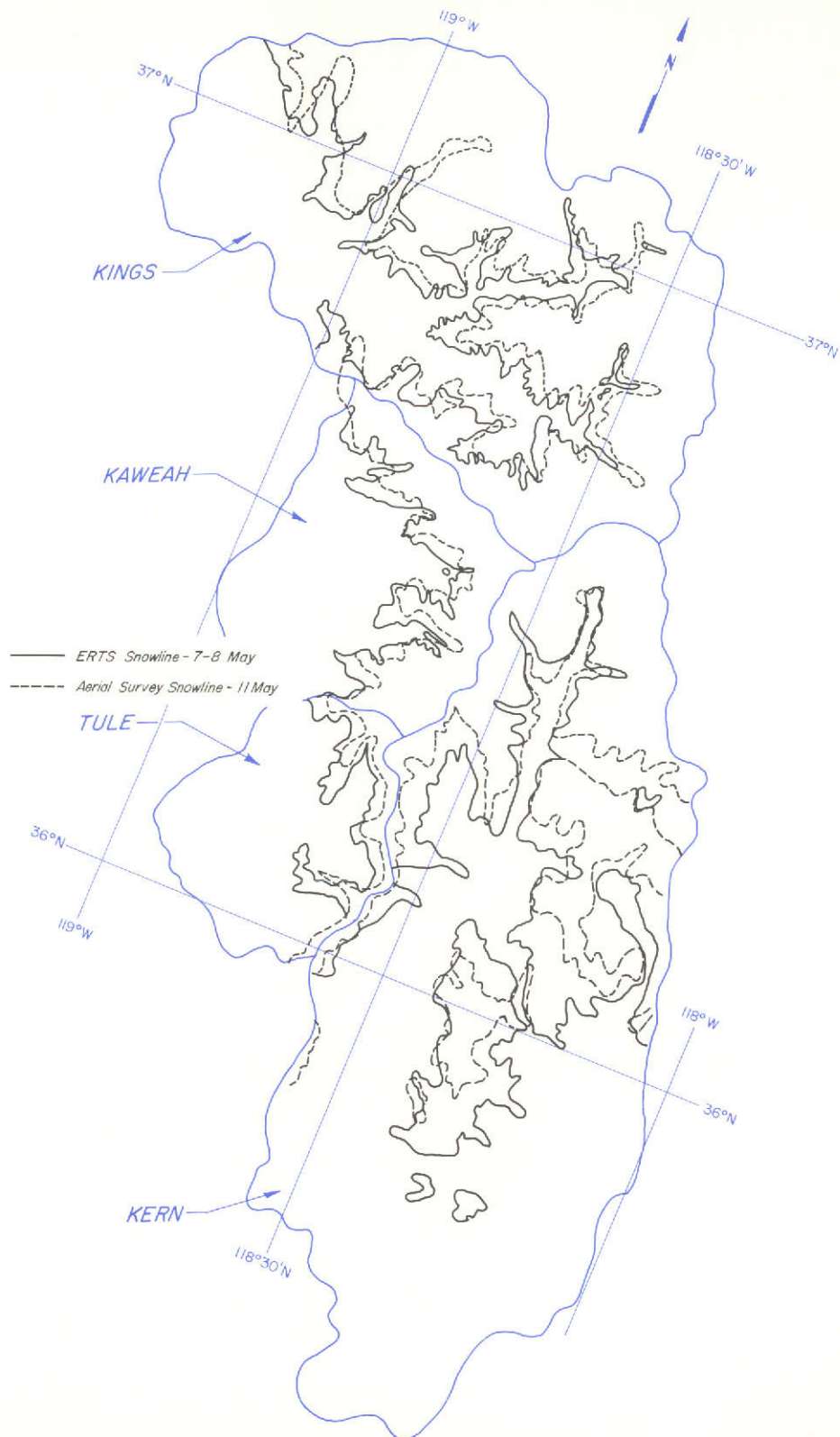Figure 5-11 Comparative map for southern Sierra Nevada test site showing
snow line mapped from ERTS imagery on 26 May and depicted on
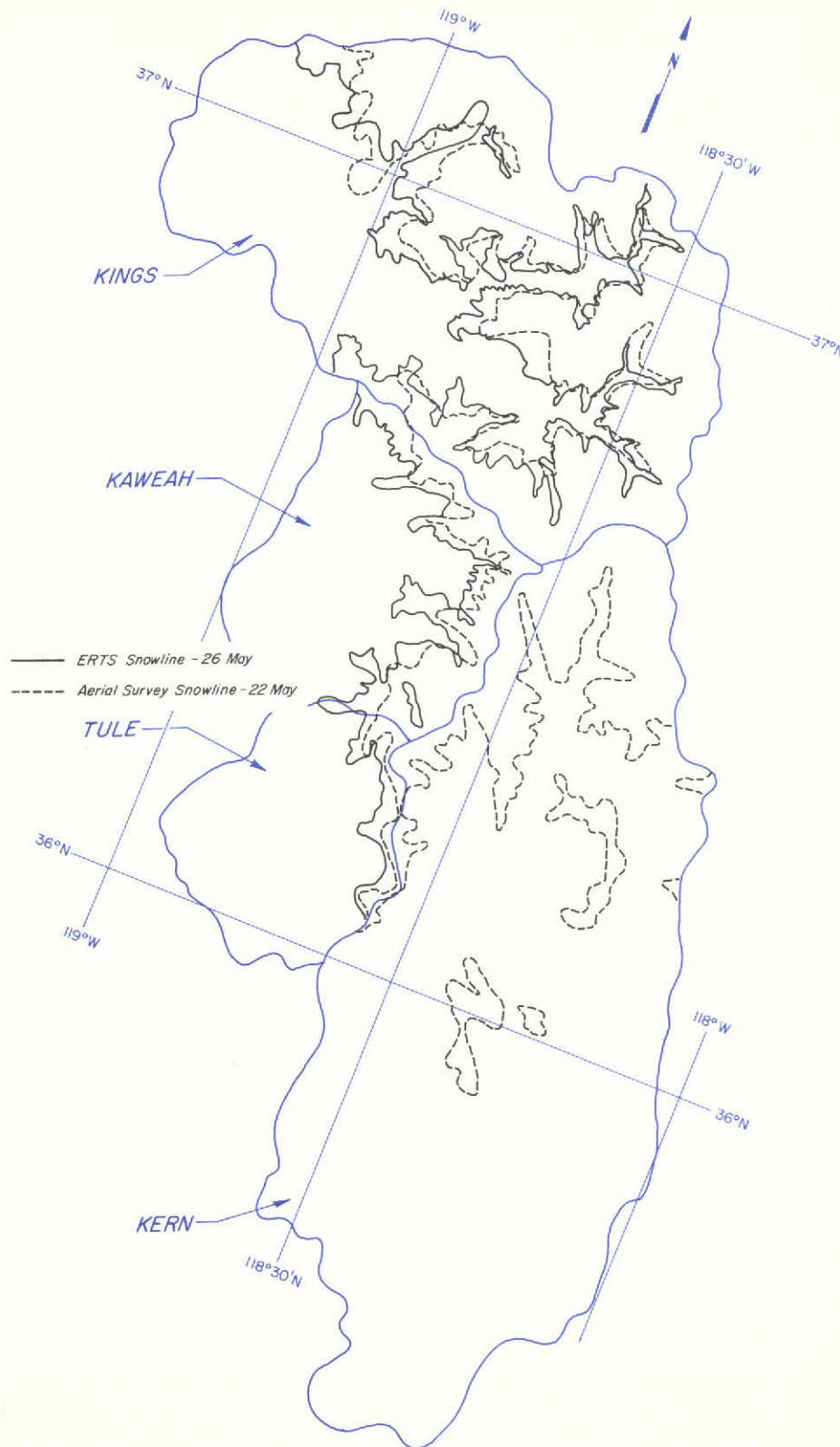aerial survey chart for 22 May.
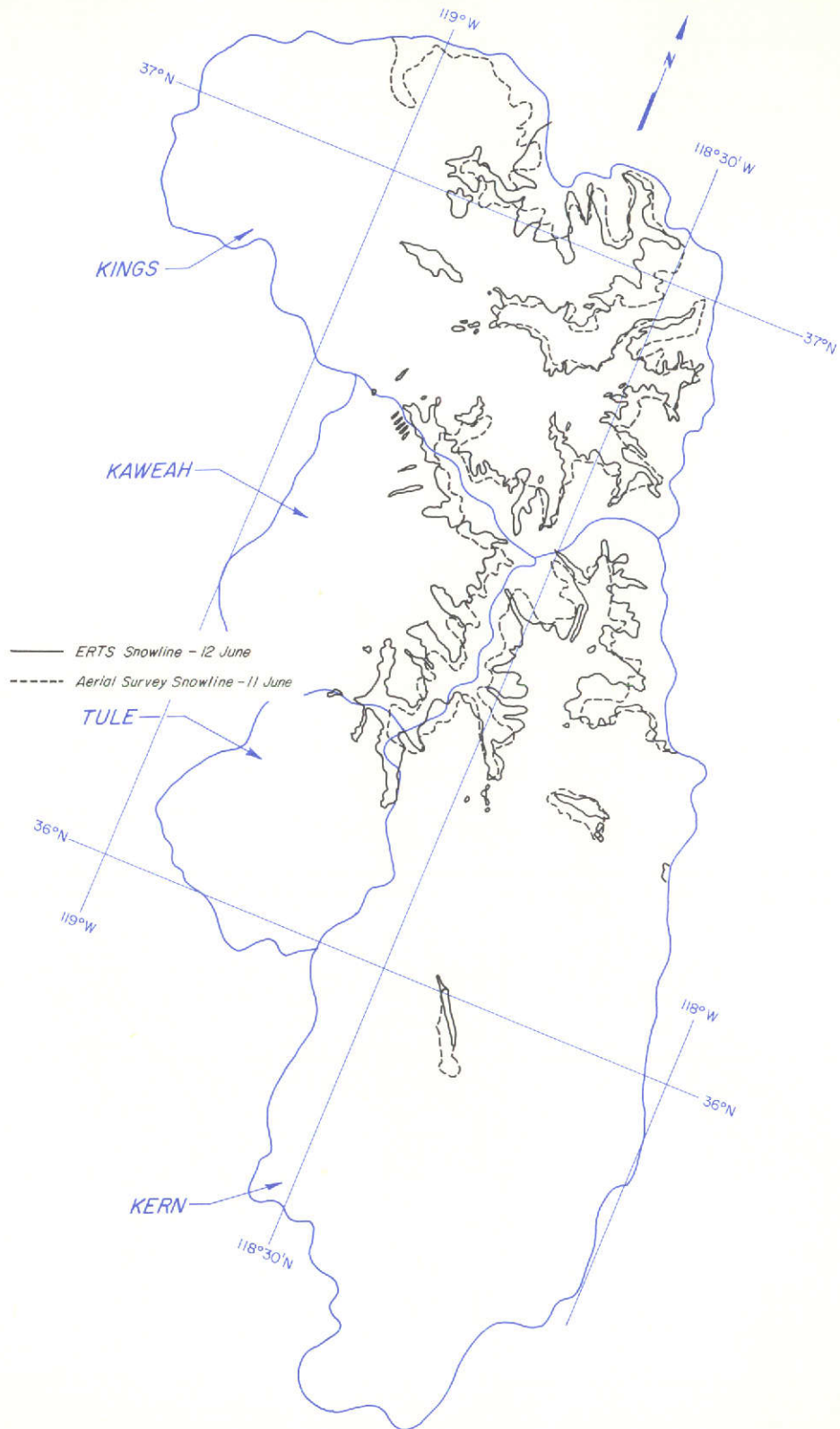
Figure 5-12   Comparative map for southern Sierra Nevada test site showing snow line mapped from ERTS imagery on 12 June and depicted on aerial survey chart for 11 June.
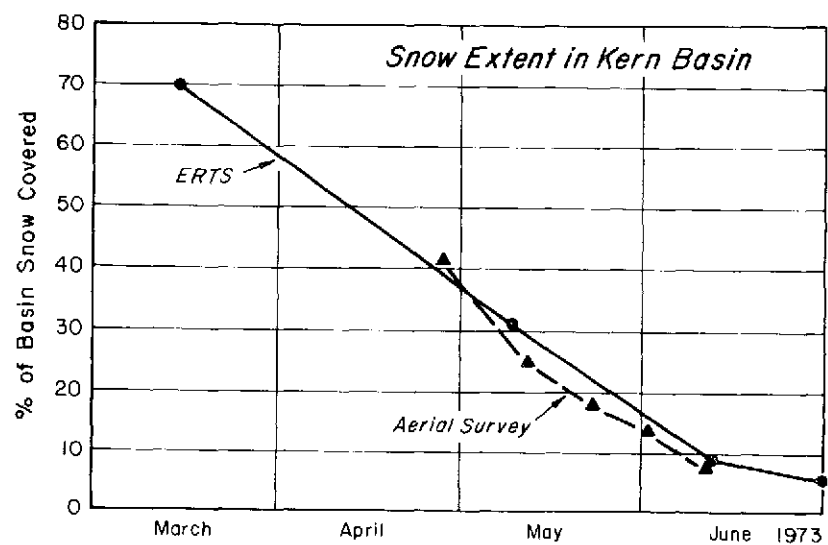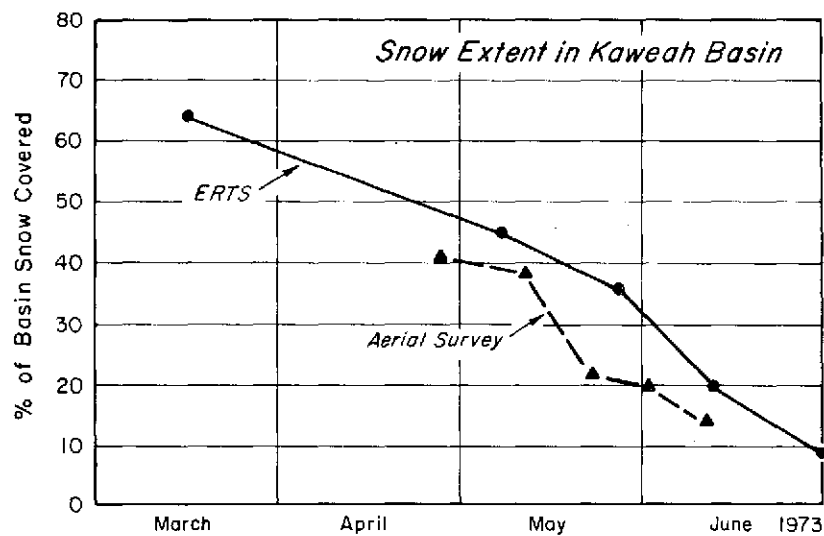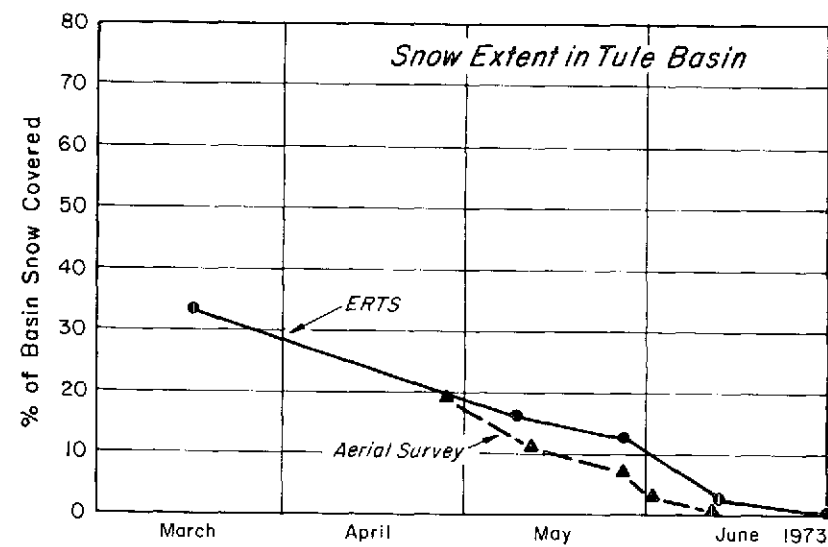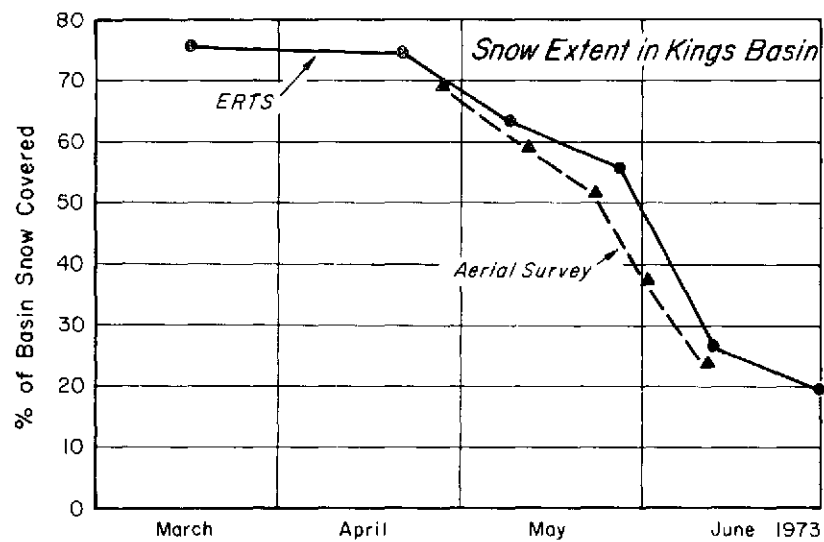
Figure 5-13 Snow extent in southern Sierra Nevada mapped from ERTS data and from aerial survey snow charts. Values are in percentage of basin snow covered; dates of observations are indicated.

TABLE 5-2

DIFFERENCE IN SNOW EXTENT IN SOUTHERN SIERRA NEVADA
MEASURED FROM ERTS AND FROM AERIAL SURVEY SNOW CHARTS

Data Sample		% Snow Cover		ESA*	
River Basin	Number of Cases	Mean Difference	Maximum Difference	Mean Difference	Maximum Difference
Kings	4	4.5%	5%	137m	152m
Kaweah	3	9.0%	14%	264m	426m
Tule	3	4.3%	6%	203m	244m
Kern	2	3.5%	6%	92m	122m

*ESA is Equivalent Snowline Altitude

The slightly greater percentage snow cover measured from the ERTS data may be the result of spring storms that deposit snow below the elevation of the substantial snowpack. Personnel at the Corps of Engineers report that in the late spring light snowfalls (a few inches) are not mapped as snowpack by the aerial observer. In the ERTS imagery, the areas covered by only a few inches of snow may still appear very bright and be mapped as the snowpack. In the case with the greatest discrepancy, however, the value derived from the aerial survey chart for the Kaweah Basin on 22 May seems to be out of line with the other values and with the values measured on that date for the other river basins (Figure 5-13). It may be, therefore, that in the Kaweah Basin the aerial survey snow line for that date is questionable rather than the ERTS analysis being in error.

5.4 Comparison Between ERTS Imagery and Aircraft Photography

In support of the ERTS investigation, high-altitude aircraft photography were collected by the NASA/ARC Earth Research Aircraft Project (ERAP) over the southern Sierra Nevada on 20 February. Three segments of the flight cross areas covered in the ERTS imagery of 25 February. Parts of two of the segments are within the four basin area, whereas the third is just northeast of that area. The segment northeast of the Kings River Basin crosses Mono Lake and the Owens River in the vicinity of Bishop. A portion of the ERTS image covering the area near Bishop is shown in Figure 5-14; the corresponding aircraft photography in approximately the same spectral band (0.58 - 0.68 μm) is shown in Figure 5-15.

In both the aircraft and ERTS data, the snow line can be identified in the area north of Bishop indicated on the topographic chart to be an area of volcanic tableland essentially unvegetated. The snow line appears to be at about the 1,500 meter level, with little change having occurred during the five-day interval between 20 and 25 February. More detail in the snow line and some patchy snow south of the edge of the solid snow cover can be mapped from the aircraft data. However, the edge of the area of significant snow cover can be mapped as precisely from ERTS as from the aircraft photography.

In another segment of the overflight, the area of the Courtright and Wishon Reservoirs in the northern Kings Basin can be identified in both the ERTS and aircraft data. The two reservoirs, which are frozen and snow covered, and the Lost Peak area in between, appear very bright. The surrounding

42
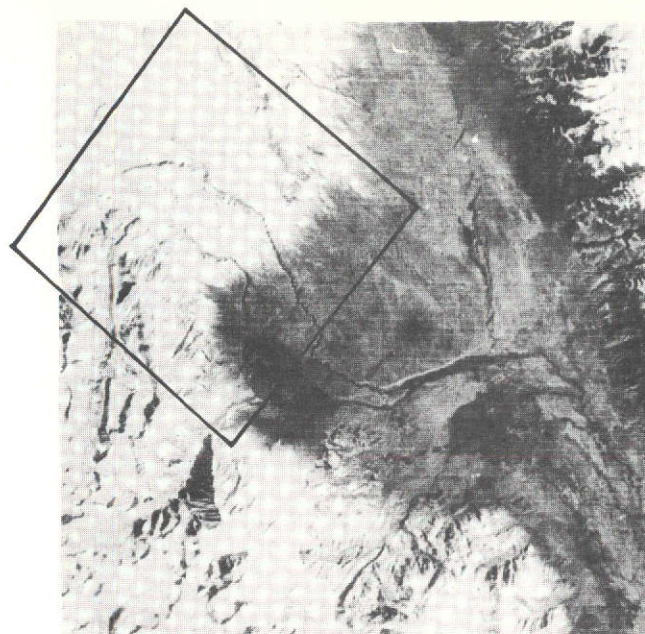
Figure 5-14   Portion of ERTS-1 MSS-5 image (ID No. 1217-18065) showing Owens
Valley near Bishop, California, 25 February 1973.   Area covered
in aircraft photograph shown in next figure is outlined.

Figure 5-15   High altitude aircraft photograph showing a part of the area
covered in the ERTS image (Figure 5-14).   Photograph was
taken on 20 February 1973.

area consists of a mixture of open and forested terrain, appearing alternately bright and very dark in the aircraft photography. In the ERTS image, the larger bright areas can be identified whereas the smaller areas are intergrated with the forested areas to produce a gray tone. It appears, therefore, that even though more detailed patterns can be identified in the aircraft data, the information content of the ERTS image with regard to mapping snow cover is equal to that of the higher resolution photography.

6.   RESULTS OF DATA ANALYSIS: SALT-VERDE
WATERSHED TEST SITE

6.1   ERTS Coverage

Snow extent for at least a portion of the Salt-Verde Watershed could
be mapped from ERTS imagery for seven of the ten repeat cycles between mid-
November 1972 and early May 1973. For each cycle the eastern third of the
watershed is covered on one day and most of the remaining part on the
following day. On one occasion (26 December) most of the area was cloud-
free, but the imagery was not of usable quality. Thus, even in a year
with much above average precipitation, the central Arizona area was suf-
ficiently cloud-free that useful snow information could be derived on
most of the potential ERTS passes.

ERTS images covering portions of the watershed on 21 November, 14
January, 19 February, and 2 May are shown in Figures 6-1 through 6-4,
respectively. The boundary of the Salt-Verde Watershed is indicated on
the images; the snow cover to the north of the boundary is in the Little
Colorado drainage basin. Snow can be identified and mapped in this test
site using the techniques described in Section 4. In Figure 6-2, for
example, the snow-covered terrain can be readily distinguished from the
clouds, which cover the area to the northeast of the mountains. In
November, Mormon Lake is not frozen and Rogers Lake is only partially
frozen; in the wintertime images these two lakes are frozen and snow
covered, but by early May are once again ice-free. Several man-made
features can be detected, including the transmission-line swath running
north-south just east of Mormon Lake. The Mogollon Rim, running along
the northern edge of the watershed, is a prominent geological feature
whose appearance is enhanced with snow cover. Variations in reflectance
related to varying amounts of forest cover are also evident in these
images.

6.2   Comparison Between ERTS Data and Aerial Survey Snow Charts

Because of the transient characteristics of the snowpack in the
Salt-Verde Watershed, aerial surveys are flown at approximately two-week
intervals throughout the winter season, and more often during periods of
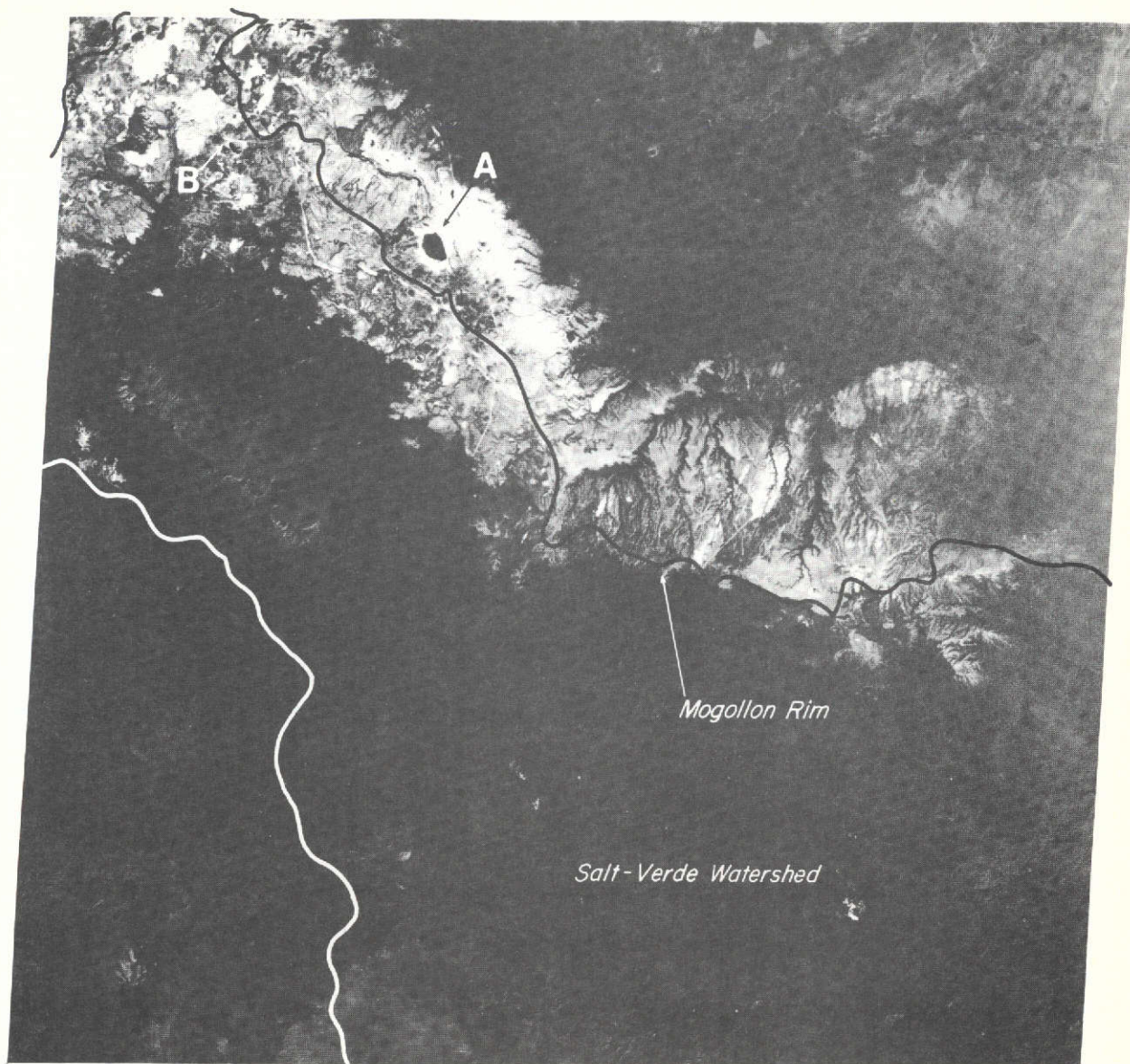
Figure 6-1   ERTS-1 MSS-5 image (ID No. 1121-17330) showing portion of Salt-Verde
Watershed, 21 November 1972. Northern part of watershed is snow
covered. Mormon Lake (A) is not frozen; Rodgers Lake (B) is partially
frozen. Watershed boundary is indicated.

Figure 6-2   ERTS-1 MSS-5 image (ID No. 1175-17324) showing portion of Salt-
Verde Watershed, 14 January 1973. Mormon and Rodgers Lakes are
frozen and snow covered. Watershed boundary is indicated. Clouds
cover the area northeast of the mountains.

Figure 6-3   ERTS-1 MSS-5 image (ID No. 1211-17332) showing portion of Salt-Verde Watershed, 19 February 1973.
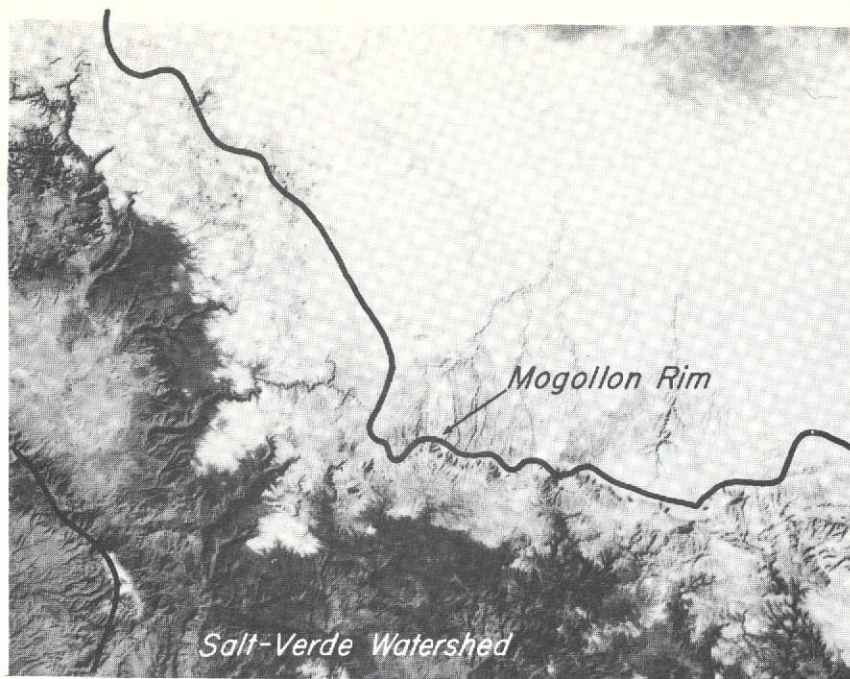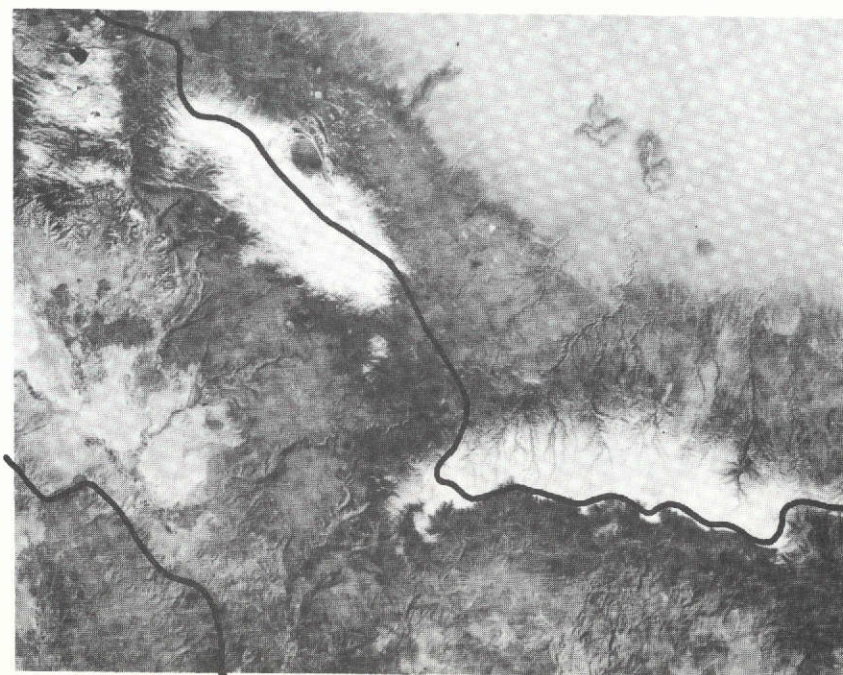

Figure 6-4   ERTS-1 MSS-5 image (ID No. 1283-17332) showing portion of Salt-Verde Watershed, 2 May 1973. Note decreased snow cover and unfrozen lakes.

rapid melt. With these charts available throughout the winter, it was possible to prepare a comparative map for each ERTS observation. The dates for which maps were prepared are given in Table 6-1, and the comparative maps are shown in Figures 6-5 through 6-11.

TABLE 6-1

DATA SAMPLE FOR SALT-VERDE WATERSHED, 1972-73

Case	Date of ERTS Photography	Date of Aerial Survey Snow Chart	Interval Between ERTS and Aerial Survey Observations (in days)
1	21 November	14 November	7
2	14 January	12 January	2
3	01 February	02 February	1
4	18-19 February	15 February	3-4
5	26 March	26 March	0
6	13 April	12 April	1
7	02 May	27 April	5

As was true for the Sierra Nevada, the comparative maps indicate that more detail in the snow line can apparently be mapped from the ERTS data than can be mapped by the aerial observer, who often views the terrain at an oblique angle and must often draw a "smoothed" snow line. Nevertheless, for all cases analyzed, the locations of the snow lines are in generally good agreement, particularly in the Verde Watershed west of about 111°, and in the easternmost part of the Salt Watershed. In nearly all areas in which a discrepancy occurs, the aerial survey chart depicts a greater snow extent than is mapped from the ERTS imagery.

The largest discrepancies can, in most instances, be accounted for by changes in snow cover that occurred during the interval between the observations. In the November case (Figure 6-5), for example, relatively light snow amounts are reported in the areas where snow is indicated on the chart but is not detectable in the ERTS image. Personnel involved in flying the aerial surveys report that the area near 34°N, 111°W is mesa

Figure 6-5   Comparative map for portion of Salt-Verde Watershed showing snow line
mapped from ERTS imagery on 21 November and depicted on aerial survey
chart for 14 November.

Figure 6-6   Comparative map for portion of Salt-Verde Watershed showing snow line
mapped from ERTS imagery on 14 January and depicted on aerial survey
chart for 12 January.

Figure 6-7   Comparative map for portion of Salt-Verde Watershed showing snow line mapped from ERTS imagery on 1 February and depicted on aerial survey chart for 2 February.

Figure 6-8   Comparative map for portion of Salt-Verde Watershed showing snow line
mapped from ERTS imagery on 18-19 February and depicted on aerial survey
chart for 15 February.

Figure 6-9   Comparative map for portion of Salt-Verde Watershed showing snow line mapped from ERTS imagery on 26 March and depicted on aerial survey chart for 26 March.

Figure 6-10 Comparative map for portion of Salt-Verde Watershed showing snow line mapped from ERTS imagery on 13 April and depicted on aerial survey chart for 12 April.

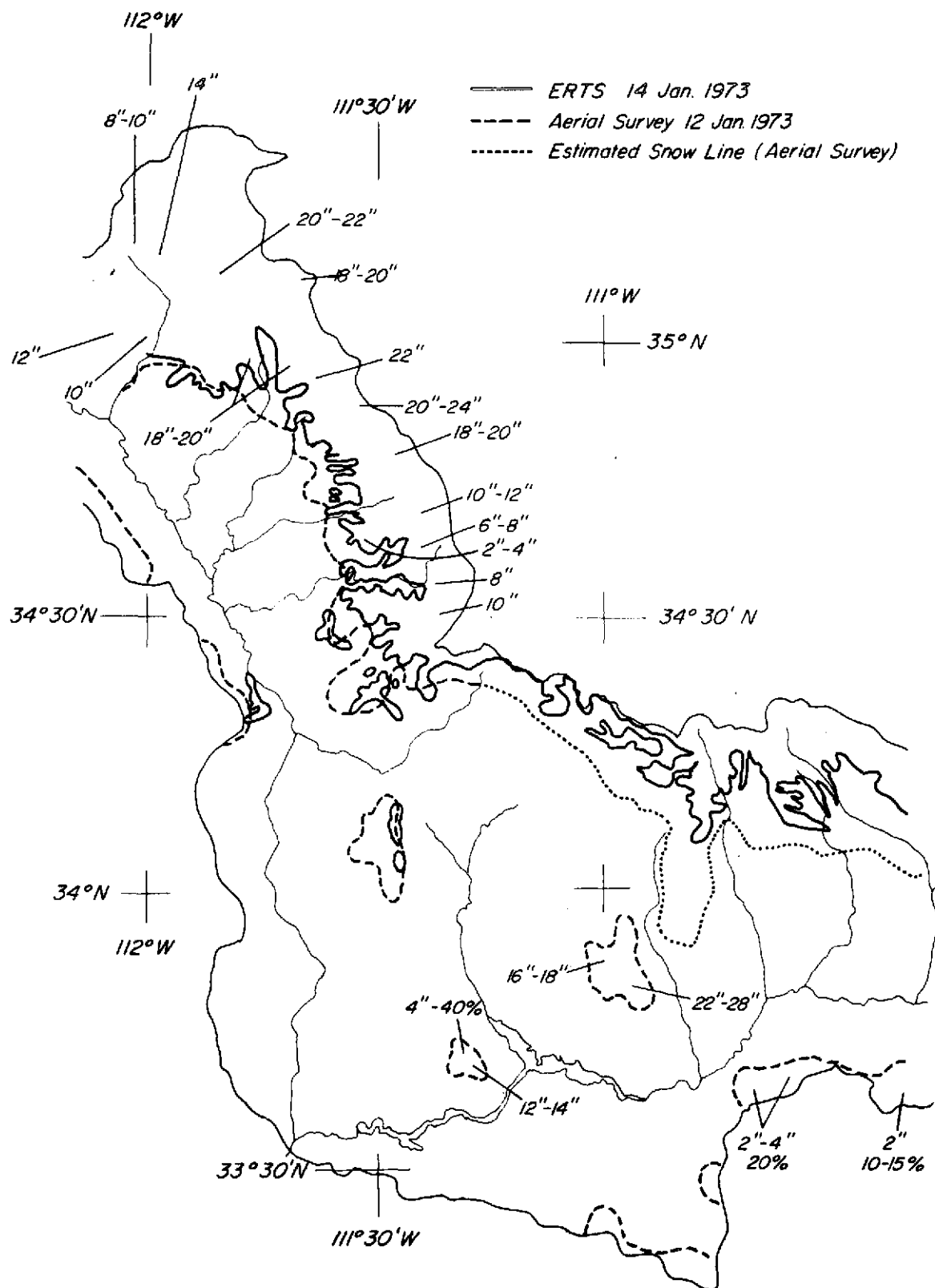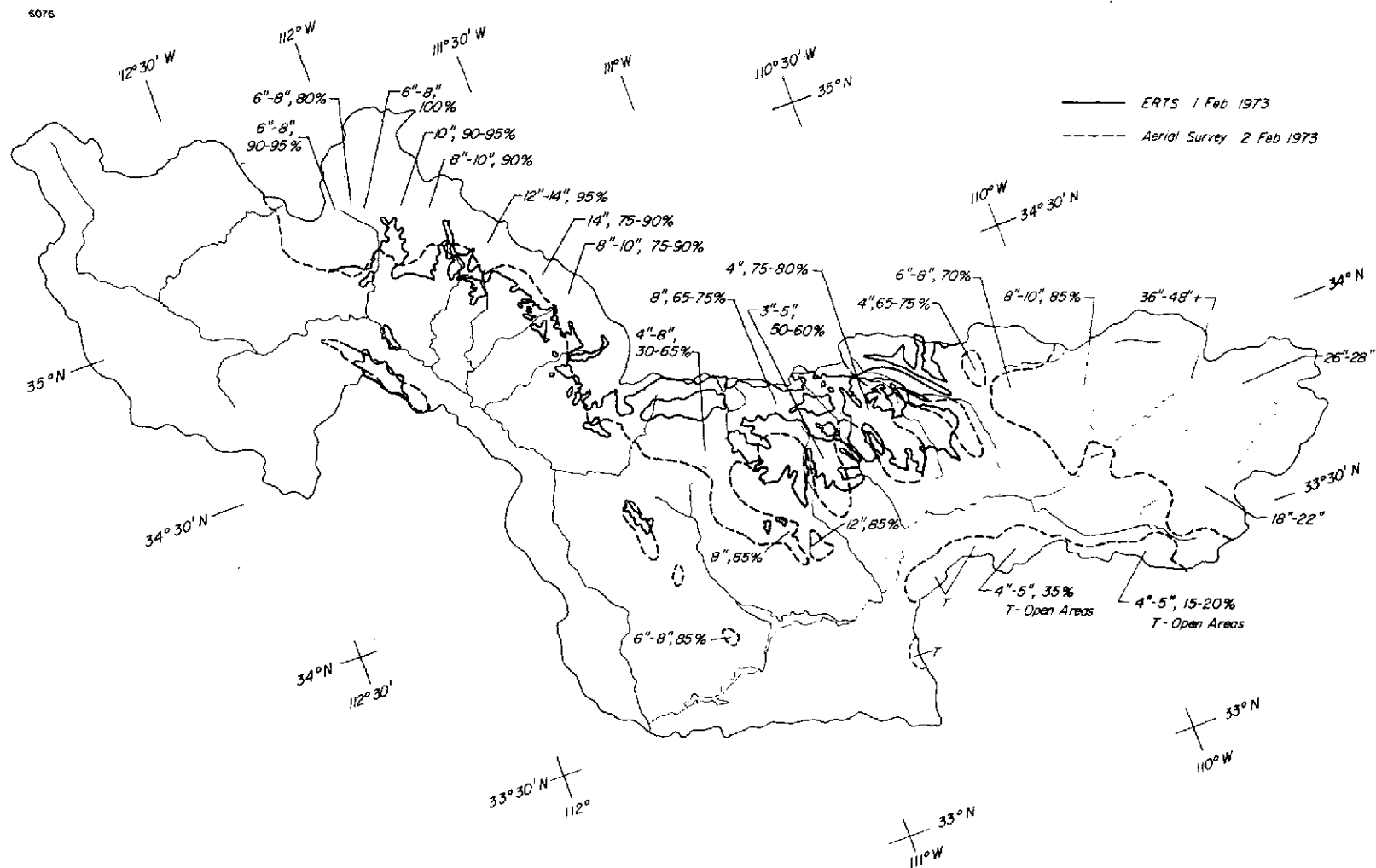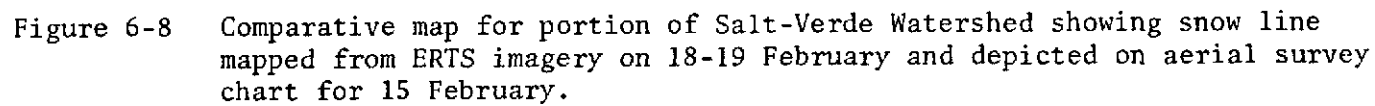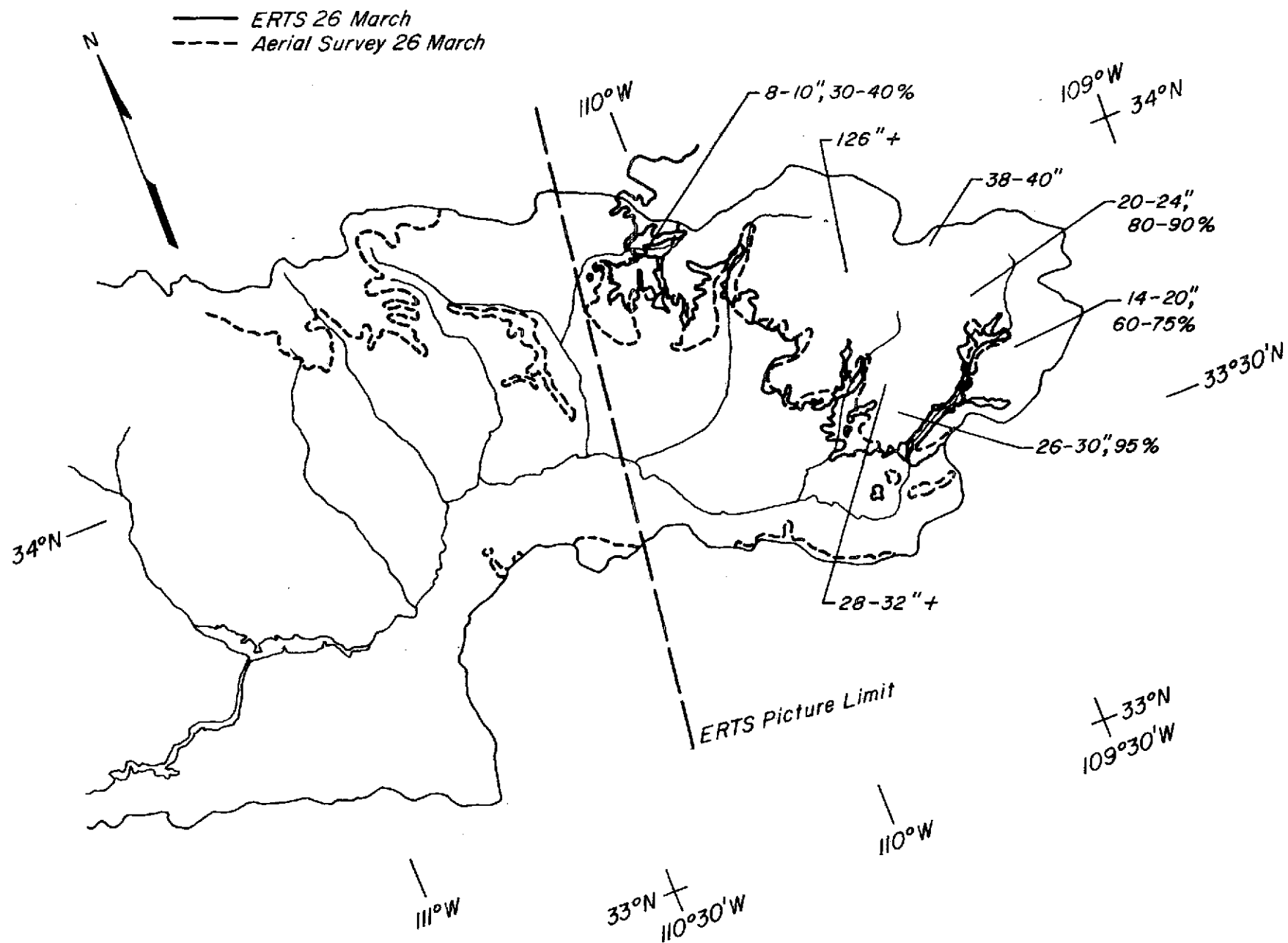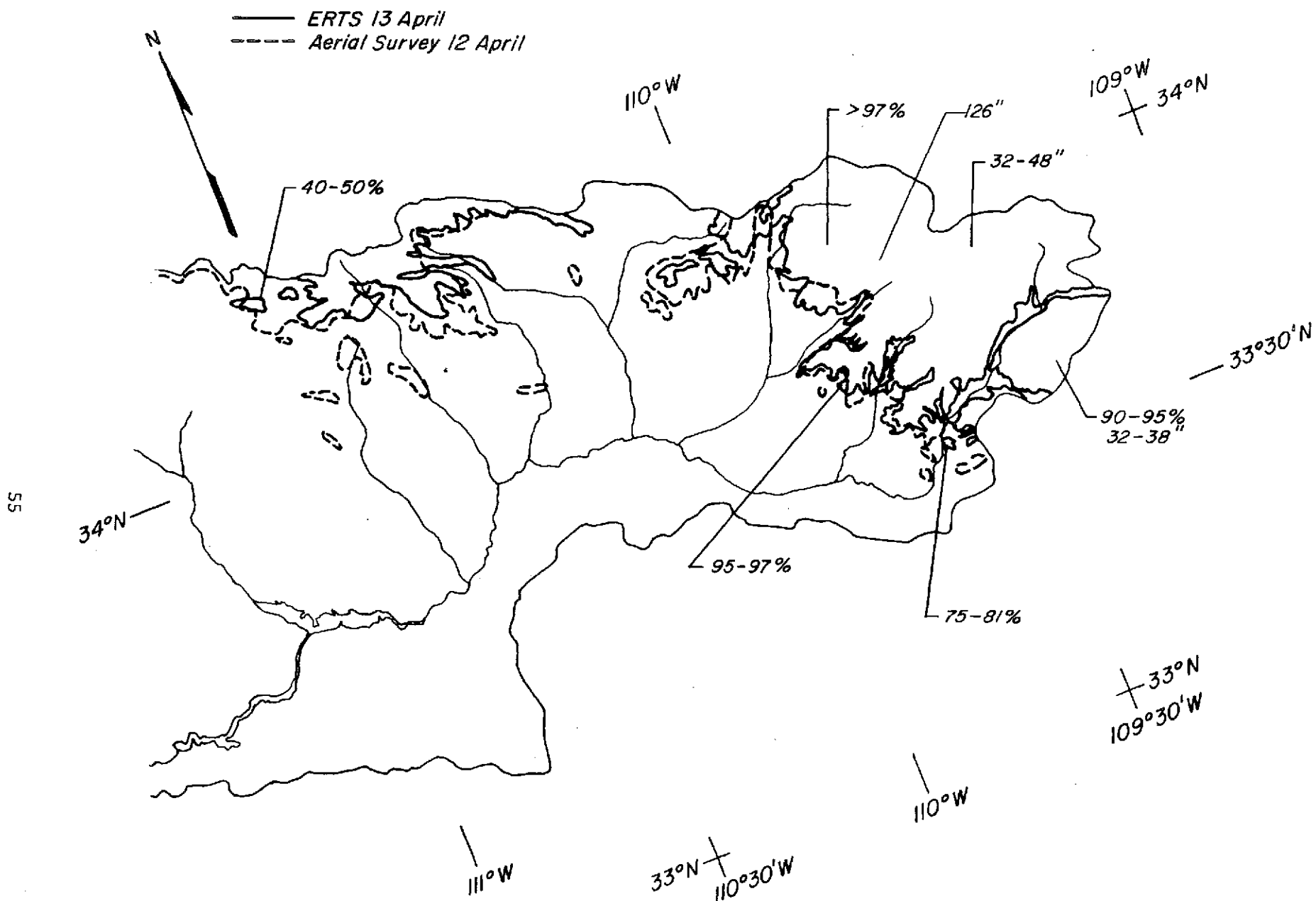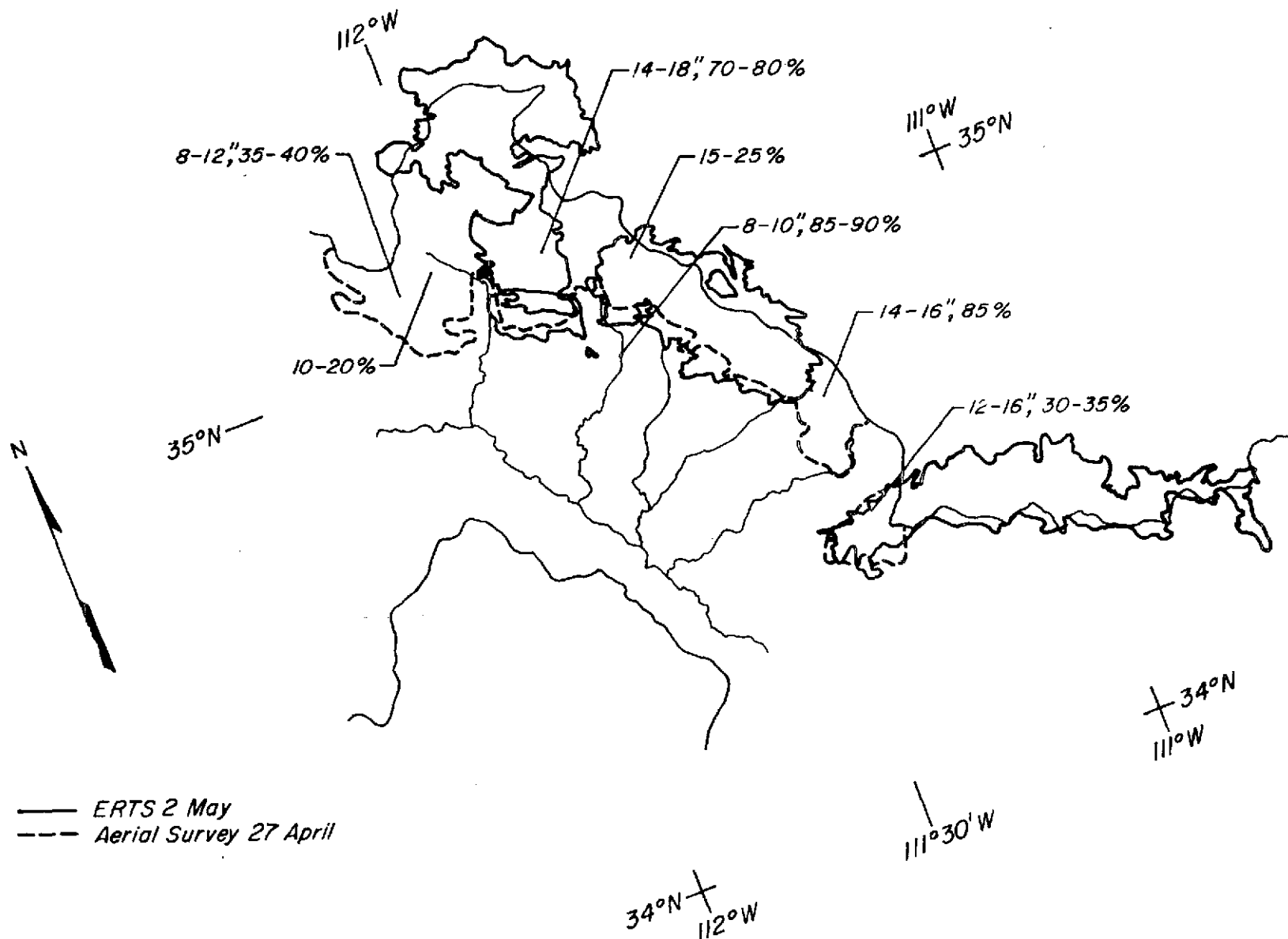Figure 6-11 Comparative map for portion of Salt-Verde Watershed showing snow
line mapped form ERTS imagery on 2 May and depicted on aerial
survey chart for 27 April.

land, where it is common for snow to melt rapidly. Since the aerial survey
chart indicates a snow depth of only a trace to 1" over much of the area on
14 November, it is quite likely that a week later the snow would be con-
fined to the higher elevations, as the ERTS data indicate. A similar situ-
ation probably exists in the late spring case (Figure 6-11), where a part
of the area within which snow cannot be detected in the ERTS image is
reported to have only a 10 to 20% snow cover.

In the early February case (Figure 6-7), the most significant dis-
crepancies occur in the area north of Roosevelt Lake (near 34°N, 111°W).
At a location where 30 to 65% snow cover of 4 to 8 inches is reported, snow
cannot be detected in the ERTS imagery. In the ERTS imagery, the snow line
appears to lie along the Mogollon Rim at an elevation of about 2100 m.
Later in February (Figure 6-8), the snow extent has increased. Although
some snowfall is indicated to have occurred between the time of the aerial
survey and the ERTS pass, very close agreement in the snow lines is observed
in the Verde and eastern Salt Watersheds. In the area north of Roosevelt
Lake, the snow cover does not appear to be continuous as is indicated in
the aerial survey chart. In the ERTS image, however, snow does appear to
exist at lower elevations to the south of the Mogollon Rim, where no
snow could be detected 18 days earlier. In this particular case, the snow
line in an area just north of the Watershed was mapped from the over-
lapping ERTS images on 18 and 19 February. The resulting map indicates
that a decrease in snow extent has occurred in the 24-hour interval between
the two ERTS passes. The apparent 24-hour snowmelt is substantiated by the
reported snowfall at Winslow; at that station four inches of snow fell on
16 and 17 February, but subsequently melted by the 18th.

To obtain a quantitative evaluation of the differences between the
ERTS data and aerial survey charts, the percentage of snow cover was
computed by planimetering the respective snow-covered areas for each case.
Because the portion of the watershed covered in the ERTS image varied
from case to case, the computations were performed for the total watershed
area that was mapped rather than for specific drainage basins. In some
cases (such as Case 4), therefore, the values represent the percentage
of snow cover within nearly the entire Salt-Verde Watershed, whereas in
others (such as Cases 5 and 6) the values are for only a portion of the
watershed. The values are given in Table 6-2.

TABLE 6-2

COMPARISON BETWEEN SNOW EXTENT MAPPED FROM ERTS IMAGERY AND AERIAL
SURVEY SNOW CHARTS FOR SALT-VERDE WATERSHED TEST SITE

Case	Percentage of Area Snow Covered		
	ERTS	Aerial Survey	Difference
1 (November)	19	33	14
2 (January)	19	26	7
3 (early February)	22	29	7
4 (late February)	39	48	9
5 (March)	51	53	2
6 (April)	25	27	2
7 (April-May)	25	36	11
MEAN DIFFERENCE FOR ALL 7 CASES:			7

Overall, the mean difference in the percentage snow cover for the
seven cases tested is 7%, with the snow extent as mapped from ERTS data
being less than that depicted on the aerial survey chart in every instance.
The greatest differences are for the two cases that have the longest time
interval between the ERTS and aerial survey observations; the smallest
differences are for the two cases during the spring for which the eastern
portion of the watershed was covered and for which the aerial survey was
flown on the same day or only one day before the ERTS observation.
Besides the explanation that actual changes in snow cover can account for
the observed differences, it may also be that in Arizona much smaller snow
amounts are mapped by the aerial observer than in the Sierras; this can
explain in part why the snow extents mapped from ERTS appear to be
slightly less than the aerial surveys in the Salt-Verde Watershed, but
generally greater than the aerial surveys in the river basins of the
southern Sierras.

6.3 Comparison Between ERTS Imagery and Aircraft Photography

On 16 March aircraft data for the central Arizona mountains were collected by the NASA/ARC Earth Resources Aircraft Project. The aircraft photography is similar to that collected over the southern Sierras. Two segments of the flight path were over or near the Salt-Verde Watershed, one crossing the Flagstaff area in the Verde Basin and the other crossing the Mt. Baldy area in the eastern Salt Basin.

The ERTS data nearest the time of the aircraft flight are for 26 March, ten days later. During the intervening period, substantial snowfall did occur (about 20 inches at Flagstaff and 13 inches at McNary); however, the snow on the ground at both stations was less on the 26th (25 and 4 inches, respectively) than on the 16th (30 and 18 inches, respectively). The most recent previous snowfalls at both stations were on 14 March, two days before the aircraft flight, and on 23 March, three days before the ERTS passage. A portion of the ERTS image for 26 March near the Mt. Baldy area is shown in Figure 6-12; the aircraft photography (the 0.690-0.760 µm spectral band product) covering the same area is shown in Figure 6-13.

In the analysis of the aircraft data enlarged prints were prepared from the 70 mm 0.580-0.680 µm and 0.690-0.760 µm spectral band film. No significant difference in the depiction of snow cover was apparent, however, in these two data products. In the procedure to map corresponding snow patterns, stereo-viewing of the RC-10 color film was found useful for identifying forest effects and the shadows associated with north-facing slopes.

As can be seen upon careful examination of Figures 6-12 and 6-13, some detailed snow features that cannot be detected in the ERTS imagery can be seen in the aircraft photography; however, it appears that all significant snow cover (i.e., substantial snow cover, not small amounts such as might be found along small topographic features) can be detected in the ERTS imagery. Furthermore, despite the smaller scale of the ERTS image, the subtle tonal differences due to forest and shadow effects can be detected; in fact, the influence of these factors on the reflectance of the snow seems to be even more pronounced in the aircraft photograph than in the ERTS image. These findings are in agreement with the results of the similar analysis carried out for the southern Sierra Nevada test site.

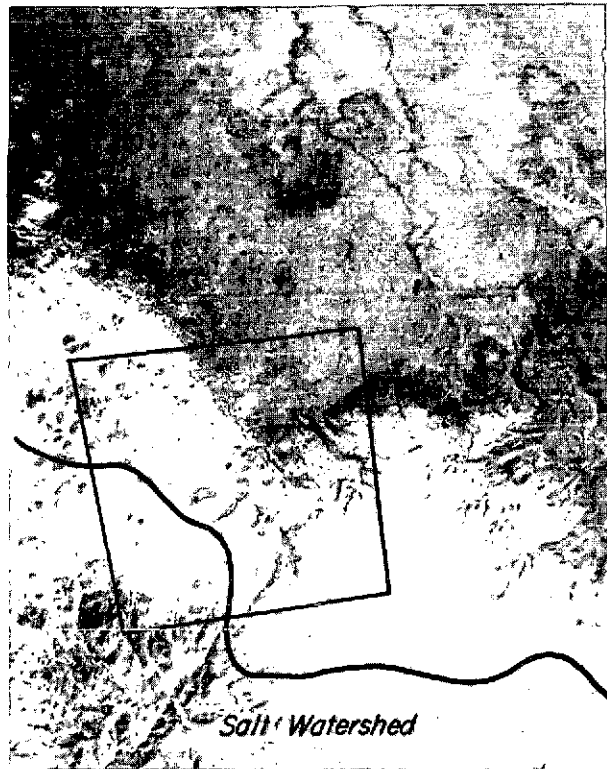Figure 6-12 Portion of ERTS-1 MSS-5 image (ID No. 1246-17274) showing snow cover near eastern end of Salt-Verde Watershed, 26 March 1973. The watershed boundary is indicated; the area covered in the aircraft photograph shown in the next figure is outlined.
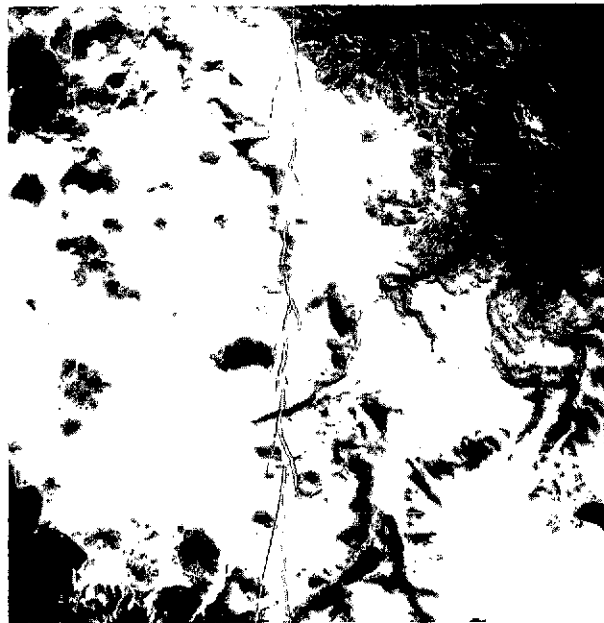

Figure 6-13 High altitude aircraft photograph showing a part of the area covered in the ERTS image (Figure 6-12). Photograph was taken on 16 March.

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7. RESULTS OF DATA ANALYSIS: ADDITIONAL TEST SITES

7.1 Cascades

Because of the mid-summer launch of ERTS-1, the only substantial snow cover existing within the United States (excluding Alaska) during the early days of ERTS operation was in the Cascade Mountains in the Pacific Northwest. As mentioned in Section 2, some of the early images covering this area were acquired even though the area was not originally selected as a test site. The purpose of acquiring these data was to perform preliminary analyses to develop interpretive techniques that could then be applied to data collected over the specified test sites.

The results of these cursory analyses will not be discussed in detail. The early analyses did demonstrate that dynamic changes in snow line elevation could be mapped from ERTS data. Using images from late July and early September 1972, snow line elevations were measured for the Olympic Mountains and the Mt. Rainier area, in Washington. A snow line retreat of approximately 300 m during the five-week period was found for both areas. The snow line in early September represents essentially the limit of the permanent snow fields. More thorough investigations of the use of ERTS data to map snow in the Cascades have been conducted by Meier (1973).

7.2 Upper Columbia Basin

A limited data analysis was undertaken for the Upper Columbia Basin in northern Idaho and western Montana, a region with forest cover that is considerably more dense than that of the southern Sierra Nevada or of central Arizona. Because of the more frequent cloud obscuration in this region, a considerably smaller amount of useable ERTS data has been available than for the Arizona and California test sites. Moreover, in the entire Columbia Basin the snowfall during the 1972-73 winter was well below normal, resulting in below normal runoff. Because of the lack of substantial snow cover, in comparison with normal conditions and, in particular, with the exceptional snowfall of the two previous years, fewer aerial snow survey flights were made by the Corps of Engineers during the 1973 spring season. Therefore, a reduced amount of correlative data were

available. The few cloud-free ERTS images that were examined are discussed in the following paragraphs.

An ERTS image on 21 January shows extensive snow cover in the area of the confluence of the Clearwater and Potlatch Rivers between Lewiston and Orafino, Idaho. The terrain in this general area consists of numerous narrow ridges and valleys, however, which produce shadow effects that make the precise mapping of snow difficult. As with the winter imagery in the Sierras, the shadow problem can be somewhat alleviated by reprocessing the images to a larger scale using a different exposure time.

In another ERTS image covering the same area on 8 February, the snow cover appears to have decreased considerably. A check of the climatological data summary for stations in the area indicates that snowmelt probably did occur during the period as the result of rather high temperatures. Imagery on 26 February indicates snow cover on only the higher elevations, and in imagery on 3 April very little snow cover can be identified.

ERTS data covering the Flathead Lake area in Montana on 19 April provide a good example of the problems of cloud obscuration that appear to be rather common in this region. In this imagery, the lower elevation terrain is essentially cloud-free; however, each mountain range, such as the Flathead Range south of the lake, is covered by cumuliform cloudiness. The extent of the clouds nearly coincides with the snow extent for this range, which can be detected in a few places through breaks in the cloud cover.

7.3 Black Hills Area

Under the scope of this investigation, it was not possible to analyze the large amount of imagery received for the Upper Mississippi-Missouri River Basins test site in the north-central part of the country. One area that was examined is the Black Hills region of South Dakota, a heavily forested area surrounded by flat, open land. Because the forest limits are well-defined, this region presents a rather unique opportunity to investigate the effects of forest cover on the detection of snow in ERTS imagery. During the 1972-73 winter, useable data were collected on five passes over the Black Hills, on 6 December, 11 and 29 January, 16 February, and 6 March. Imagery from these passes was assembled, and snow cover maps for the nearest dates were obtained from the Kansas City River Forecast Center. Examination of these images showed varying snow cover conditions,

ranging from complete snow cover throughout the region on 11 January, to bare ground, except in the Black Hills area itself, on 6 March. The snow cover maps substantiate the conditions apparent in the imagery.

The results of the analysis of imagery on these five dates indicate that snow can be detected in the Black Hills only within the areas that are not forested. A careful examination of the tonal patterns revealed that in every instance the areas of high reflectance, some as small as approximately 300 m in width, are areas indicated on topographic maps to be grasslands, lakes, or the locations of towns. The changes in the reflectance of the terrain indicated to be forest covered are essentially undetectable through visual analysis of the imagery display, despite the reported variations in snow depth. The overall brightness of the Black Hills region, for example, is somewhat higher on 11 January than on 6 December only because the brightness of non-forested terrain has increased with the greater snow amount.

8. MULTISPECTRAL DATA ANALYSIS

8.1 Analysis of Near-IR (MSS-7) Data

In an investigation of the application of ERTS data for mapping sea ice (Barnes and Bowley, 1973b), the combined use of the visible (MSS-5) and near-IR (MSS-7) spectral bands has been found to be extremely useful for distinguishing ice types. Similarly, snow lines on arctic glaciers can be detected by comparing the visible and near-IR bands. In the California and Arizona test sites, contrast between snow and bare ground is considerably lower in the MSS-7 than in the MSS-5 imagery. Despite the lower contrast, however, the snow line in the wintertime images can be mapped from the MSS-7, and the snow extent appears to be about the same as determined from the MSS-5 data.

In some late spring cases, the areas appearing very bright in MSS-7 are smaller than those appearing bright in MSS-5. For example, in the Kern Basin on 30 June, the brightest tones in MSS-7 are limited to the highest ridges, whereas in MSS-5 a distinctly larger area appears to be snow-covered; the MSS-5 and MSS-7 images for this date are shown in Figure 8-1. The apparent snow extent was mapped from each of these images, and the areas were planimetered to determine the percentage snow cover within each drainage basin. The results, given in Table 8-1, substantiate the differences that are apparent in the visual examination of the imagery.

In the investigation of arctic sea ice, the lower reflectance in the near-IR spectral band in certain instances has been attributed to the existence of meltwater on the ice surface. A wet snow surface would presumably also have a lower reflectance in the near-IR; this was observed to be true in the near-IR imagery from the Nimbus-3 satellite (Strong, et al, 1971). In the 30 June case, the snow visible in the MSS-7 image may be the high-elevation dry snow, whereas both the dry and lower elevation wet snow surfaces are visible in the MSS-5 image. Thus, the combined use of the visible and near-IR ERTS data may have application for distinguishing areas of melting snow.
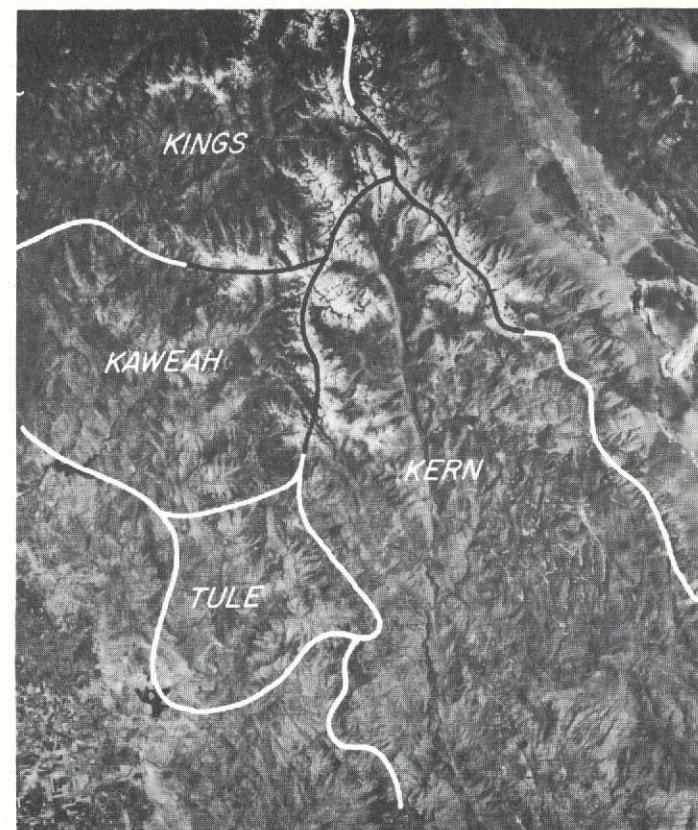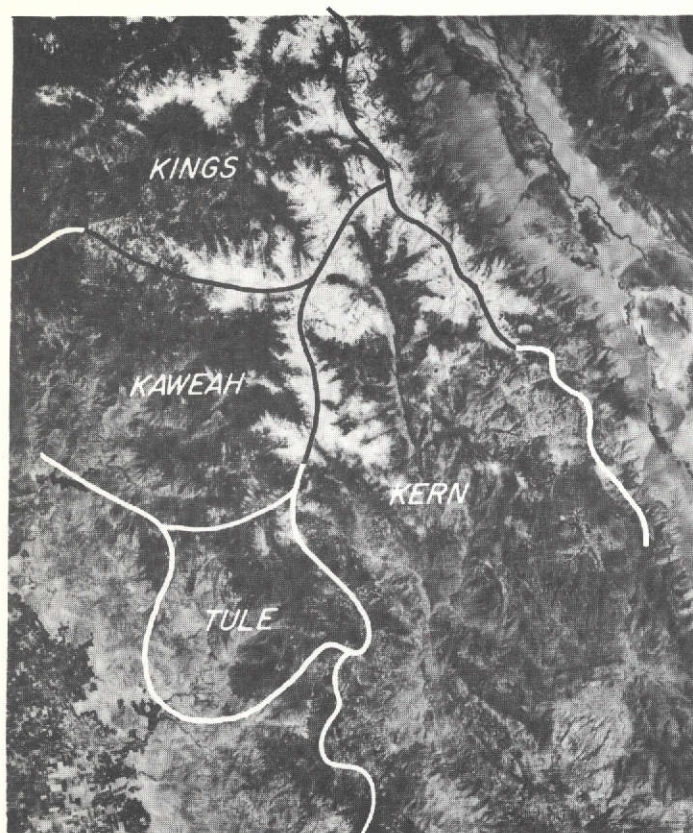
Figure 8-1   ERTS-1 MSS-5 (left) and MSS-7 (right) images (ID No. 1342-18010) showing southern Sierra Nevada, 30 June 1973. River basin boundaries are indicated. Note the lesser apparent snow cover in the near-IR band (MSS-7) as compared to the visible band (MSS-5).

TABLE 8-1

SNOW EXTENT MEASURED FROM MSS-5 AND MSS-7 IMAGES, 30 JUNE 1973,
SOUTHERN SIERRA NEVADA TEST SITE

Drainage Basin	Snow Extent (km^2)		Percentage of Basin Snow-Covered	
	MSS-5	MSS-7	MSS-5	MSS-7
Kings[1]	559	281	24	12
Kaweah	135	88	9	6
Tule[2]	–	–	–	–
Kern	341	216	6	4

[1]Only a portion of the Kings Basin was mapped; the MSS-7 image was not available for the northern part of the basin.

[2]The Tule Basin was not mapped because of insufficient snow cover.

8.2   Analysis of Color Composite Data

Color composite transparancies were examined for the southern Sierra Nevada and Salt-Verde Watershed test sites, as well as for the Black Hills area.   The color composites acquired from the NDPF were the standard product produced using the MSS-4, MSS-5, and MSS-7 bands.   Overall, certain features can be more easily identified in the color than in the black and white products; these features include rivers, lakes, and some vegetation boundaries.   In most areas, however, the snow line can be mapped as accurately from the MSS-5 black and white product as from the color composite product.

Color composite data are useful for distinguishing areas that consist of patchy snow surrounded by highly reflective rock surfaces as opposed to continuous snow cover.   An example is the 16 September 1972 case for the southern Sierras, the MSS-5 image for which is given in Figure 5-1. Color composite products for 16 September and for 8 May are given in Figures 8-2 and 8-3, respectively.

Interpretation of the extent of the snow cover in the Sierras is ambiguous in the image given in Figure 5-1. However, examination of the color products shows rather clearly that the areas that could be mapped as continuous snow based on the black and white image alone actually consist mostly of snow-free terrain. In the May image (Figure 8-3), areas of continuous snow cover appear distinctly "whiter" than does even the highest elevation terrain in the September case (Figure 8-2).

Color composite data may also have advantages for distinguishing snow in mountain shadow areas. In the midwinter imagery, areas in the Kings River Basin that are snow covered but in shadow appear in a slightly bluish color tone, whereas the terrain that is below the snow line appears in a brownish color tone. On the other hand, in the Black Hills region the color composite imagery does not seem to offer any significant improvement for detecting snow in the heavily forested terrain.
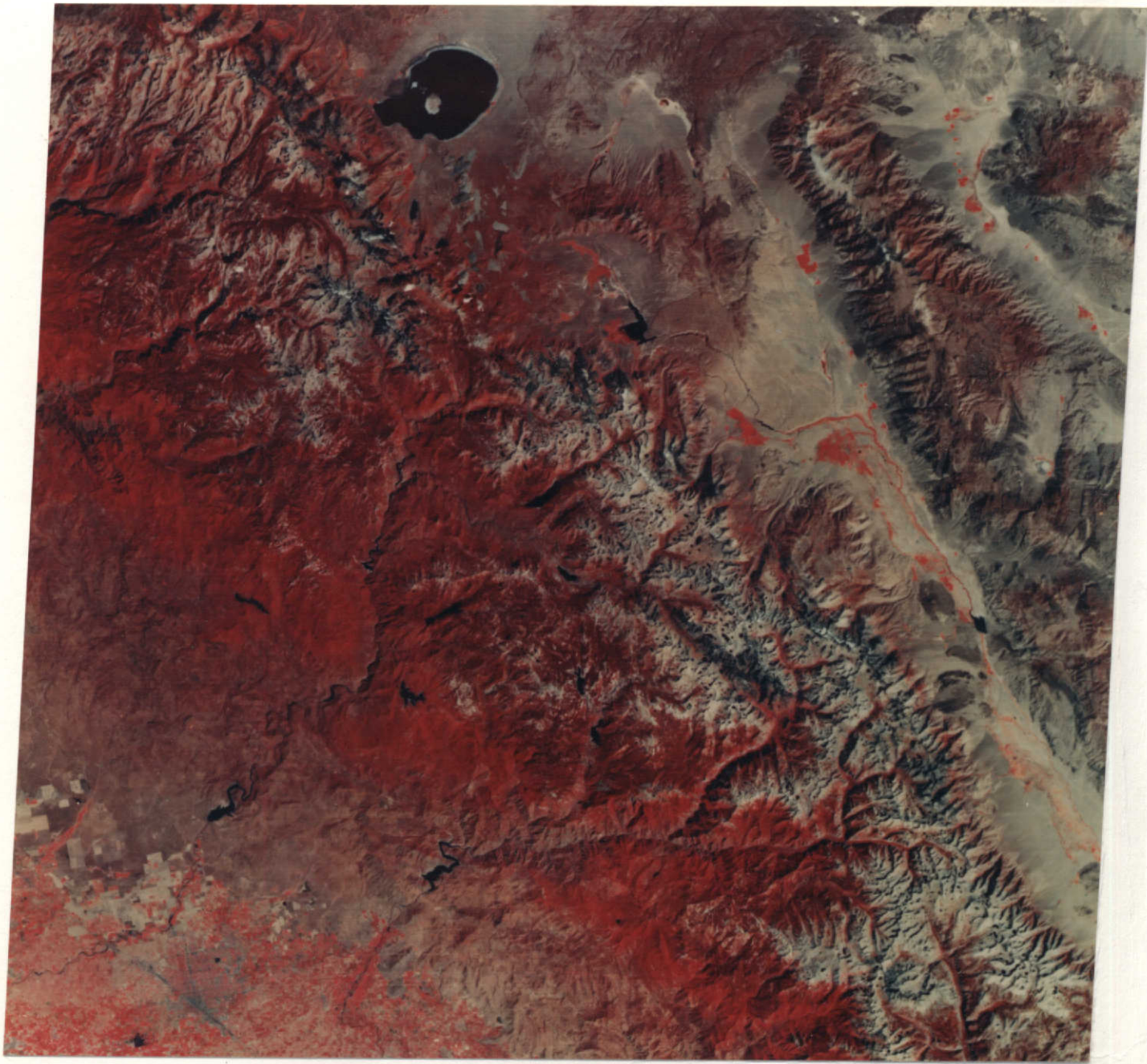
Figure 8-2   ERTS-1 color composite image (ID No. 1055-18055), showing southern
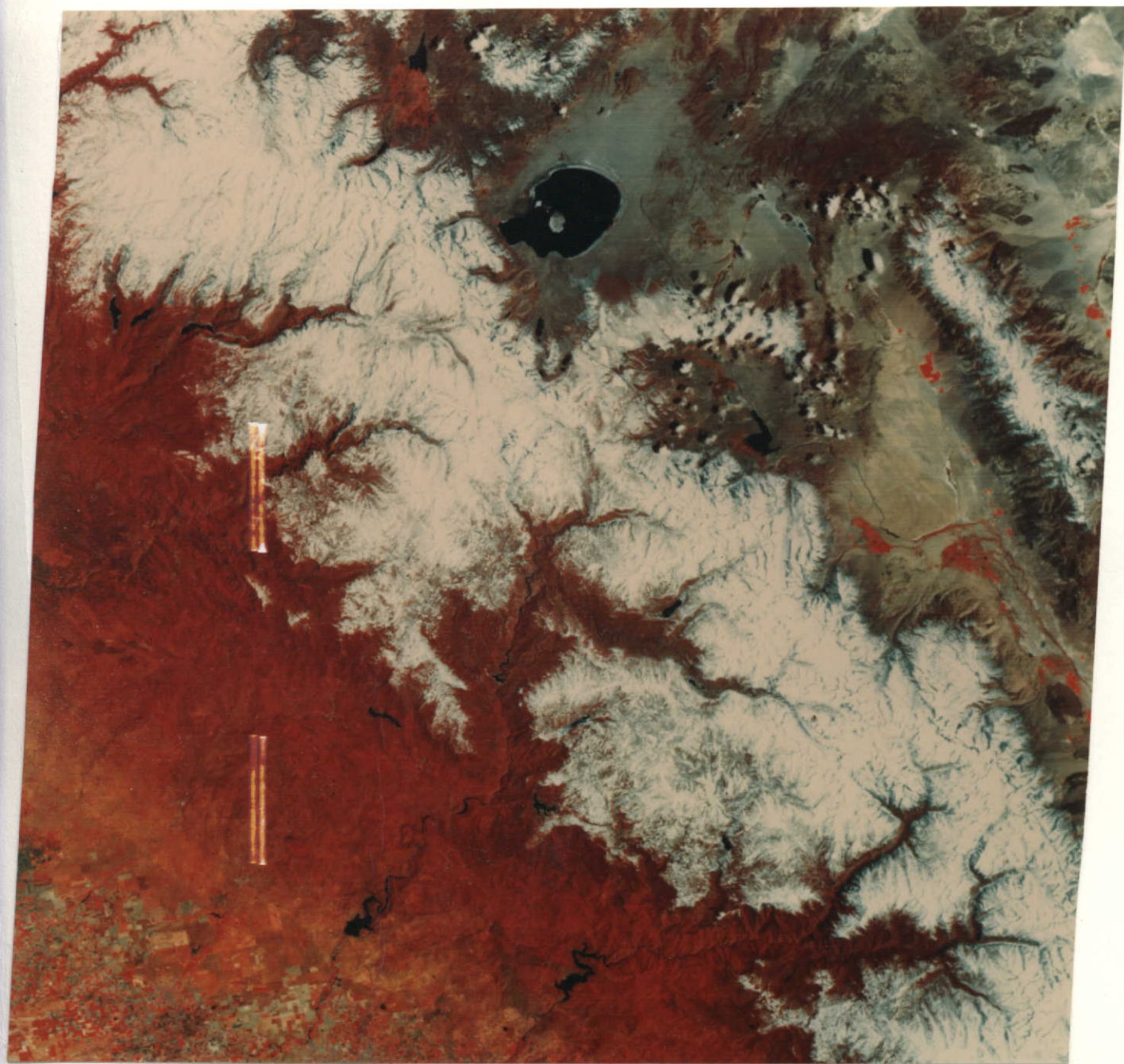Sierra Nevada, 16 September 1972.

Figure 8-3   ERTS-1 color composite image (ID No. 1289-18065), showing
              southern Sierra Nevada, 8 May 1973. Note the "whiter" tone
              of the snow as compared to the color tone of the September
              image (Figure 8-2).

9. CONCLUSIONS

9.1 Practical Applications Resulting from the Use of ERTS Data for Snow Mapping

Based on the results of the analysis of ERTS-1 imagery collected during the 1972-73 winter season over two primary test sites in the western United States, (the southern Sierra Nevada in California and the Salt-Verde Watershed in central Arizona), it is concluded that the amount of information in ERTS imagery with practical application to snow mapping is substantial. Of the four ERTS-1 MSS spectral bands, the MSS-5 (0.6-0.7 μm) band is the most useful for snow mapping; in the MSS-5 imagery mountain snow cover can be readily detected and can be distinguished from clouds through a number of interpretive keys. Moreover, for the two test sites, both of which are areas where snow hydrology is a major concern, useful snow cover information could be derived from ERTS data on 70 to 80 percent of the repeat cycles during the sample period. Thus, in these two areas, cloud obscuration does not appear to be a serious deterrent to the use of satellite data for snow survey.

The results of the analysis of ERTS imagery for the Arizona and California test sites indicate that the extent of the mountain snowpacks can be mapped from ERTS data in more detail than is depicted in aerial survey snow charts. In fact, in discussions with personnel who are responsible for making aerial surveys in the Salt-Verde Watershed, it was pointed out that in at least one instance during the 1972-73 snow season a significant amount of snowmelt runoff was "wasted" because of the inherent accuracies of existing data collection methods; with better information on snow conditions, such as might have been provided by ERTS data, it is possible that a management decision could have been made so that the runoff could have been diverted to a power-generating station to produce revenue rather than simply being released to flow downstream.

In four river basins of the southern Sierra Nevada, the agreement between the percentage of the basin snow covered as measured from ERTS and from the aerial survey charts is of the order of 5 percent for all cases except one. Moreover, in both test sites, significant discrepancies between the ERTS and aerial survey data can usually be explained by changes in

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snow cover during the interval between the two observations. In the
southern Sierras the snow extent mapped from ERTS is consistently some-
what greater than that depicted on aerial survey snow charts; in central
Arizona the opposite is generally true. This difference may in part be the
result of differing observing techniques used by the aerial observers in
the two areas.

In addition to comparative analysis with aerial snow charts, the ERTS
data have also been compared with high-altitude aircraft photography. The
results of the comparative analysis indicate that although small details
in the snow line that cannot be detected in the ERTS data can be mapped from
the higher-resolution aircraft data, the boundaries of the areas of
significant snow cover can be mapped as accurately from the ERTS imagery
as from the aircraft photography. There is also evidence that the
combined use of visible and near-IR imagery may have application for
distinguishing areas of melting snow. Color composite data also appear
to have advantages for detecting snow in certain conditions; however,
the information content of the more readily available black and white imagery
is sufficient for most snow mapping purposes.

The costs involved in deriving snow extent maps from ERTS imagery
appear to be very reasonable in comparison with current data collection
methods. For example, the flight time to survey the Salt-Verde Water-
shed is approximately five hours, with another hour or so needed to compile
the snow chart. On the other hand, the snow extent can be mapped from an
ERTS image covering nearly the entire watershed area by an experienced
analyst in about two hours. Eventual machine processing can be expected
to reduce this time considerably.

9.2 Recommendations

The major drawbacks to the use of ERTS data as input to an operational
system are the availability of the data and the rate of repetitive coverage.
To be useful operationally the data would have to be made available to the
user within twenty-four hours. The rate of repetitive coverage in the
central Arizona area, where snowmelt can occur rapidly, would ideally have
to be of the order of less than one week. In the southern Sierras, aerial
surveys are normally conducted bi-weekly; thus, in that area a repetitive

rate of coverage of the order of one week appears to be sufficient, allowing for the possibility of some data being cloud obscured. In some geographic regions, such as the Cascades and the Upper Columbia River Basin, cloud obscuration is a more serious problem than in the more southern regions.

The snow mapping techniques developed in this investigation should be tested using data from another winter-spring season. Assuming that ERTS-1 will continue to function satisfactorily, data will be available through the 1974 snowmelt period; in some geographic areas the snow cover during the 1973-74 season may be quite different from that of the previous year. Analysis of ERTS imagery for a second year will be useful to evaluate the mapping accuracies attained in the first sample period and to determine whether annual variations in snow distribution can be accurately measured.

The spatial resolution of the ERTS-1 sensors appears adequate for snow mapping purposes. However, certain problems inherent in the use of satellite data to survey snow do require further study. It remains difficult to identify snow reliably in densely forested areas, and the existence of mountain shadows can cause ambiguous results. Both of these problems currently require some degree of subjective interpretation by the analyst, and, thus, must be carefully considered before automatic processing techniques can be applied. Further investigation using the digitized data products will provide quantitative information on the effects of these factors and on the multispectral snow signatures.

Snow is a water resource for which spacecraft observation already has practical applications. The continued development of improved spacecraft mapping techniques will lead eventually to a more cost-effective means for monitoring snow cover distribution.

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11. ACKNOWLEDGEMENTS