AN EVALUATION OF EARTH RESOURCES TECHNOLOGY SATELLITE (ERTS-1) IMAGERY FOR DELINEATING SNOW EXTENT: CRATER LAKE NATIONAL PARK, OREGON

PAUL W. ROSE

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by

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A THESIS

submitted to

THE DEPARTMENT OF GEOGRAPHY

OREGON STATE UNIVERSITY

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

MAY 1975

The following professors were members of the graduate committee for Paul W. Rose and participated in the final oral examinations:

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Date: May 9, 1975

Typed by Luanne E. Beller

ACKNOWLEDGMENTS

I wish to express sincere gratitude to Dr. James F. Lahey, major professor, for his continual encouragement and guidance in designing and implementing this research. His contribution during this endeavor has made my association with him a most rewarding and memorable experience. Through his insight and efforts he has clearly demonstrated how education can be extended far beyond the classroom.

Appreciation is also extended to Keith Sandifer, doctoral graduate student, for his cartographic consultations during the drafting of the photo-mosaic map of Crater Lake and for his dark room expertise and assistance which enabled the photographs to be reproduced for this thesis.

I would also like to express my appreciation to the Environmental Remote Sensing Applications Laboratory (ERSAL), Corvallis, Oregon, especially to Gary Benson and Barry Schrumpf, for allowing me to utilize their facilities and for providing the high flight color infrared aerial photographs which were reproduced for this research.

Special thanks are extended to Mrs. Elva Michael, National Park Service employee, Crater Lake National Park, for providing pertinent snow and weather data for that area.

Finally, I would like to express sincere appreciation to my parents, Jean and Henry Rose, for their continual patience, understanding and encouragement throughout my entire academic career. This thesis is dedicated to them.

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AN EVALUATION OF EARTH RESOURCES TECHNOLOGY SATELLITE (ERTS-1) IMAGERY FOR DELINEATING SNOW EXTENT: CRATER LAKE NATIONAL PARK, OREGON

ABSTRACT: In the Pacific Northwest snow is an important natural resource. The inability to accurately measure or monitor this resource throughout remote areas is a hindrance to water management. ERTS-1 imagery provides the capability for extracting a significant amount of scientific information and data regarding snow conditions in accessible and inaccessible regions of the Pacific Northwest. The area examined to evaluate the utility of the ERTS system was in Crater Lake National Park, Oregon. The actual boundaries of the study area were determined by available high flight aerial photographs. An analysis was made for the snow conditions in the study area and factors affecting snow pack depletion were considered. High flight aerial photographs and ERTS-1 multispectral images were utilized throughout this research. The procedure followed a systematic approach establishing "ground truth" with the aerial photographs. The results from these examinations were then directly applied to the ERTS-1 images. It was determined that ERTS-1 imagery; 1) can be accurately utilized at a much larger scale (1:130,000) than was previously believed by other major researchers; 2) bands 4, 5, and 6 can be used to define maximum snow extent; 3) bands 6 and 7 delimit open areas which are snow covered; 4) rock outcroppings devoid of snow can be determined utilizing band 6; and 5) melting snow is indicated on band 7. These results have potential in the field of snow hydrology for the application of ERTS-1 images to snow pack monitoring, determining areas of concern in "the source area concept," and estimating snowmelt and stream runoff.

I. INTRODUCTION

Snow is an important natural resource in the Pacific Northwest. The inability to accurately measure or monitor this resource throughout remote areas is a hindrance to water management. In areas such as the western United States where most of the water utilized comes from mountain snow packs, a method of accurate measurement is essential for the monitoring of this resource. The ability to acquire information on the distribution and amounts of precipitation, snow-water content, stream flow rates and to accurately map snow cover is necessary for mans social and economic welfare. Because of the economic and time elements, a comprehensive or repetitive survey of the snow hydrologic parameter over large areas is impractical by conventional ground-based methods. However, orbital remote sensing satellites can provide a significant amount of scientific information and data regarding snow conditions in accessible and inaccessible regions of the Pacific Northwest. One such satellite of particular interest to snow hydrologists is the Earth Resources Technology Satellite (ERTS-1).

On July 23, 1972, the first ERTS satellite was launched into a circular sun-synchronous orbit at an altitude of 900 km above the earth. The ERTS-1 satellite rotates about the earth every 103 minutes, completing fourteen orbits per day, repeating a given orbital track every eighteen days. Aboard the ERTS-1 satellite is a scientific package of instruments which includes three boresighted return-beam vidicon (RBV) cameras. Each of these cameras records imagery in a distinctive spectral band, also aboard is a multispectral scanner (MSS) which records the imagery in four separate wavelength bands (MSS-4, 0.5 to 0.6 μm; MSS-5, 0.6 to 0.7 μm; MSS-6, 0.7 to 0.8 μm; and MSS-7, 0.8 to 1.1 μm).

The purpose of this research is to evaluate ERTS-1 imagery for delineating snow extent. Conventional high flight aerial photographs will be utilized to establish "ground-truth" in the study area. The snow cover at Crater Lake will be delineated and mapped from these high flight photographs. This information will then be directly applied to the satellite images and interpretation of the potential application of ERTS-1 imagery to the field of snow hydrology will be formulated.

II. SETTING: CRATER LAKE NATIONAL PARK

Geography

Crater Lake National Park is situated in the southern High Cascade Mountains of south-central Oregon. The park has a total area of 250 square miles and is located within Klamath County and adjacent to Douglas and Jackson Counties, Oregon (figure 1). The area is accessible by U.S. highway 62 and Oregon State highways 230 and 138.

The study area examined within Crater Lake National Park was determined by the available high flight (U-2) aerial photographs taken on July 3, 1974 (figure 2). The area delineated by these aerial photographs lies between the latitudes of 42° 51' N and 42° 50' N and the longitudes of 121° 58' W. and 122° 16' W.

Geology

The High Cascade Mountains trend in a north-south direction and extend from Mount Baker in northern Washington, to include Lassen Peak in northern California. These mountains are a part of the Pacific "Ring of Fire" and associated with this occurrence are volcanic peaks which dominate the landscape. The volcanic activity of the High Cascades occurred during the Pliocene and younger periods of the geologic time column.

During this period of time a volcanic peak from 10,000 to 12,000 feet in height developed within the present day boundary of Crater Lake National Park. This volcano,

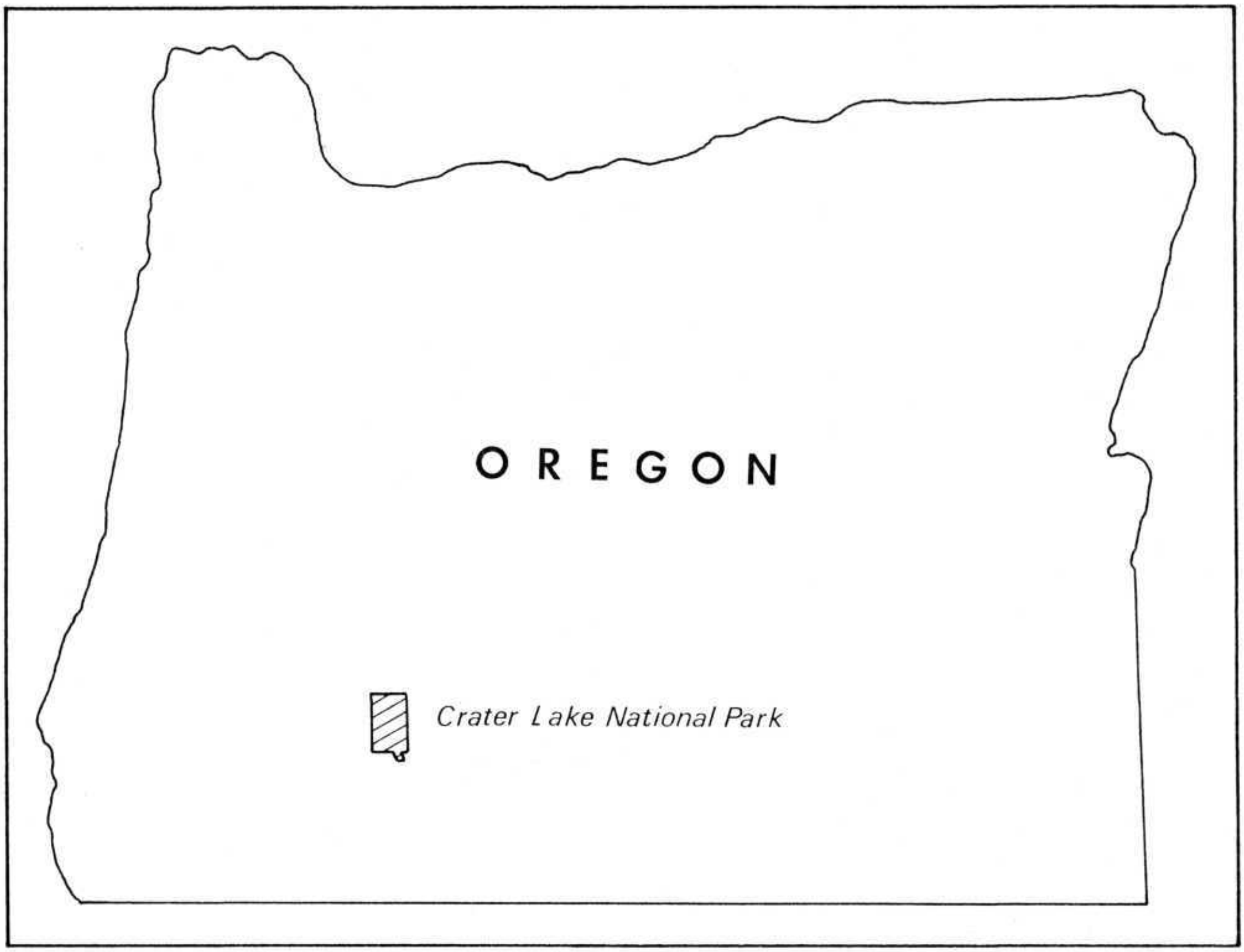


Figure 1-A: Location of Crater Lake National Park, Oregon.

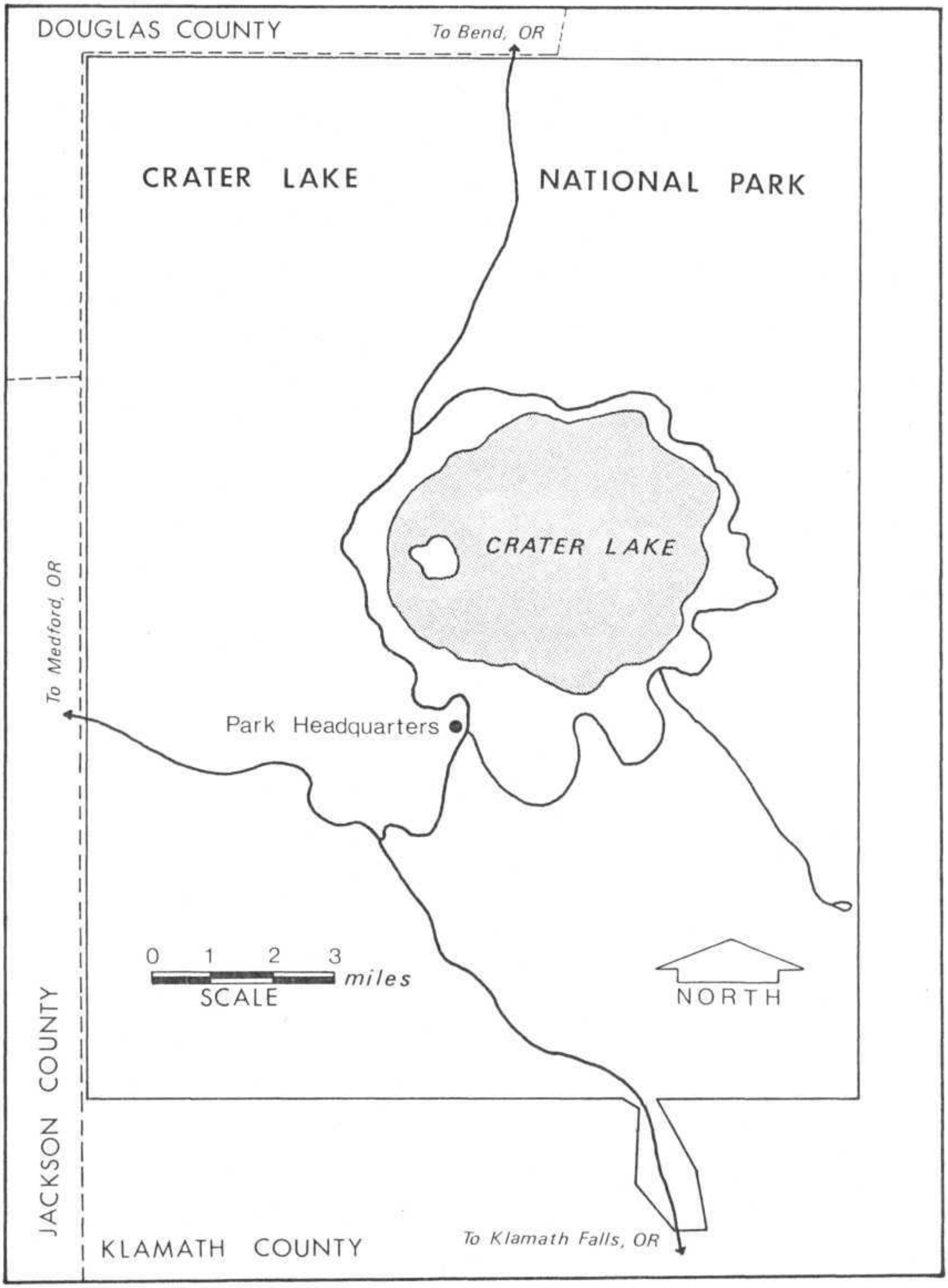


Figure 1-B: Map of Crater Lake National Park, Oregon.

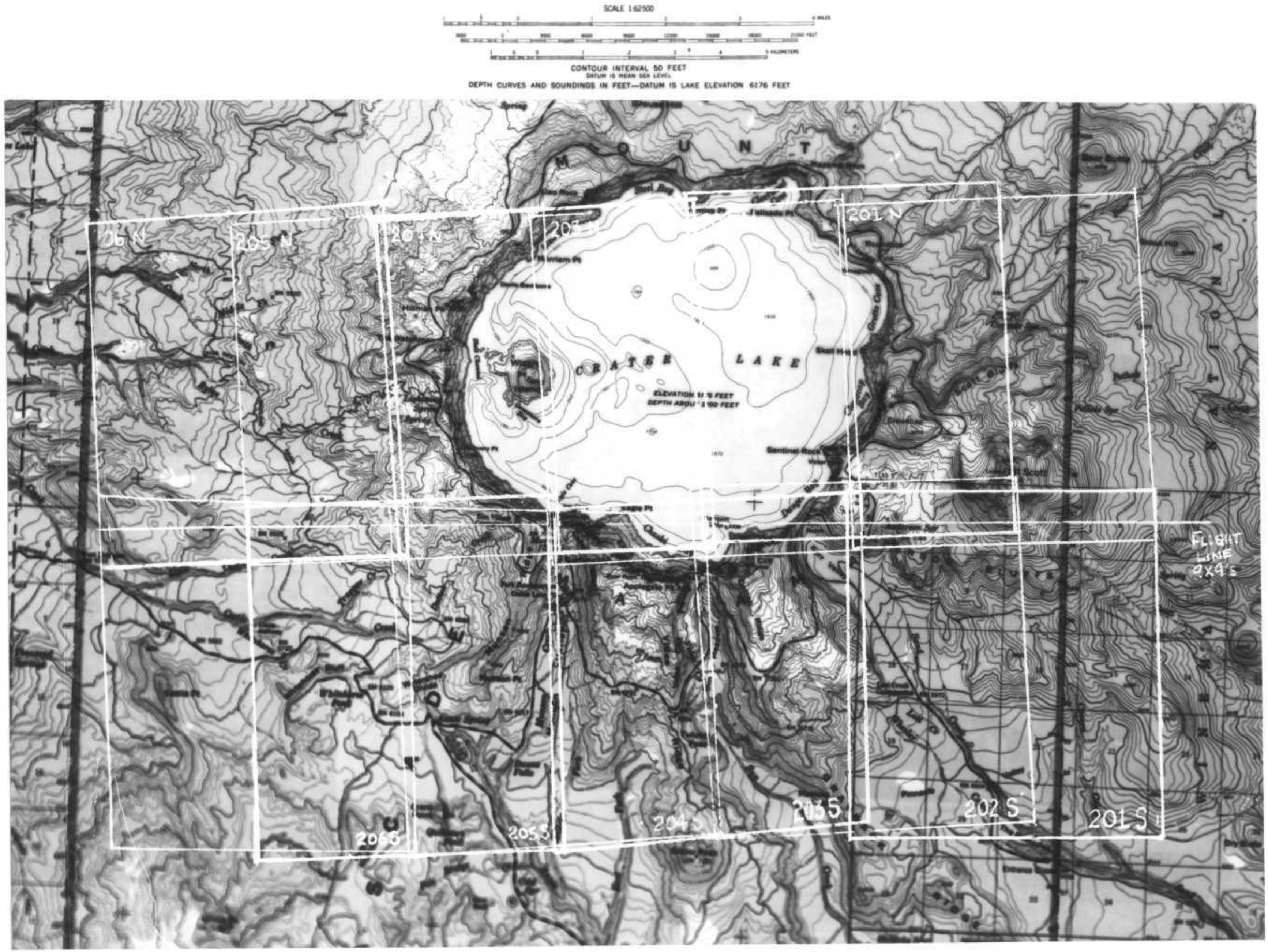


Figure 2: High flight (U-2) aerial photo coverage of the study area.

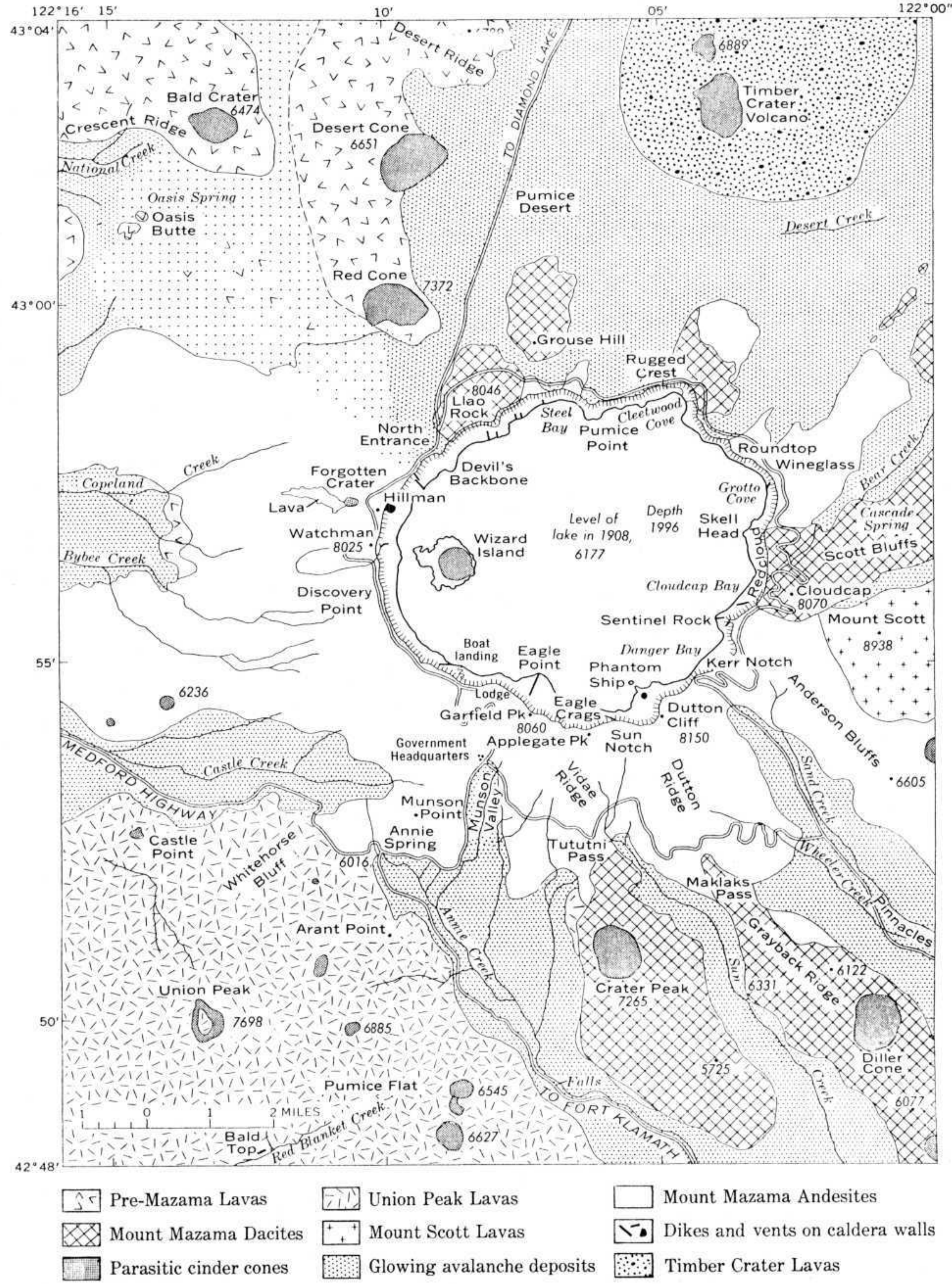
known as Mount Mazama, erupted so much material that the sides and top could no longer be supported and eventually collapsed forming a large caldera. Today, the caldera is the basin in which Crater Lake is situated.

The surficial petrology within the study area and surrounding Crater Lake is mostly a result of the ejecta issued from the volcanic vents of Mount Mazama. There are two rock types which prevail throughout the study area: andesites and pumice (figure 3). The andesites were issued during early eruptions from the summit vents of Mount Mazama. Conversely, the pumice was deposited as ejecta and from nuée ardentes flows during the culminating stage of volcanic activity. These latter deposits obscured most of the earlier andesitic flows and the original physiographic features of Mount Mazama.

Physiography

The present physiography of Crater Lake National Park is quite diverse and interrelated to the eruptions and collapse of Mount Mazama. The study area contains two specific physiographic units which influence the snow accumulation and ablation throughout the year. These two units are: 1) the caldera, and 2) the slopes of Mount Mazama which radiate from the caldera.

The caldera is the steep sided physiographic unit which circumscribes the shore line of Crater Lake. The average height of the caldera above the present shore line



Generalized geologic map of Crater Lake and Vicinity. Plate 3, Carnegie Inst. of Washington Pub. No. 540, 1942.

Figure 3: Geologic Map of Crater Lake National Park with the study area delineated by the black line.[1]

of Crater Lake is 1000 feet. However, the caldera varies in height above the shore line of the lake. For example, near Hillman Peak, on the western side of Crater Lake, the caldera reaches its maximum height of 2000 feet above the lake, whereas near Kerr Notch, on the south eastern side of Crater Lake, the caldera is only 550 feet above the lake level.

The major rock outcroppings within the caldera are deposites of andesite, dacite and pumice. The andesites and dacites usually occur as precipitous outcroppings. During most of the year snow does not accumulate on these cliffs because of the severe steepness maintained by the integrity of outcrops.

The pumice slopes throughout the caldera are much less severe. However, in many cases the pumice slope has reached its maximum angle of repose. These established slope angles then directly influence snow accumulation and ablation.

Snow accumulation develops on the pumice slopes of the caldera that have been incised by erosive forces. Snow avalanches, which are frequent in these areas, add to the total snow accumulation. Occasionally, large snow patches develop at the toe of the slope near the lake level due to these snow avalanches.

The lower slopes of Mount Mazama, which radiate out from the caldera, comprise the other major physiographic unit within the study area. This area consists of gentle slopes which dip toward lower elevations surrounding the park. Despite their general appearance, these slopes have major differences in relief due to escarpments of andesites, deeply incised pumice valleys and numerous parasitic cones.

These significant changes in relief and elevation have influenced the flora of the area. The forests are comprised of a mixture of Rocky Mountain vegetation and west coast coniferous forests. The principal communities are hemlock/pine and pine/fir associations. Both the vegetation type and density, combined with relief differences and slope aspect, influence the accumulation and distribution of snow in the study area.

Climate

The climate of Crater Lake National Park is influenced by the changes in elevation throughout the park. Associated with the differences in local relief are significant changes in precipitation distribution and temperature variance. In the study area, relief varies from a low of 5000 feet near the western border to 8926 feet at Mount Scott, which is the highest point in Crater Lake National Park.

Even though Crater Lake is situated south of the track for intense winter storm systems which strike the Pacific Northwest Coast, the climate of the area is influenced by these systems. Saturated air masses rapidly cool as they encounter the uplifted High Cascade Mountains. This orographic effect creates intense winter storms over Crater Lake National Park.

Daily climatological data is collected by National Park Service personnel at Park Headquarters which is located at an elevation of 6475 feet above mean sea level (figure 1). Approximately 70 percent of all precipitation occurs between the months of November and March. Most of this precipitation falls as snow producing deep snow packs. The mean annual snow fall for Crater Lake National Park exceeds 575 inches and each winter the accumulation of snow averages between 100 and 200 inches of snow per year.[2]

During the winter of 1973 to 1974 Crater Lake National Park received a total of 620 inches of precipitation (table 1). Snow began to accumulate at Park Headquarters on October 22, 1973, and continued to increase until a maximum depth of 214 inches had been reached. Following the period of maximum accumulation the snow pack began to ablate on April 2, 1974. Ablation exceeded accumulation until the snow pack had been completely depleted at Park Headquarters on July 13, 1974 (figure 4).[3]

The temperatures associated with the snow accumulation/ ablation period were normal during the 1973-74 winter. As would be expected, the relationship between temperatures and snow pack was inversely proportional (table 2). Snow accumulation was greatest during periods of cooler monthly temperatures and conversely, snow pack depletion occurred during periods of higher temperatures.

TABLE 1--MONTHLY PRECIPITATION RECORDED AT PARK HEADQUARTERS FOR THE WINTER OF 1973-1974

MONTH	RAIN, MELTED SNOW, ETC. (Inches and Hundredths)	SNOW, ICE PELLETS, HAIL (Inches and Tenths)
October	6.14	26.0
November	24.16	162.0
December	14.58	100.5
January	12.95	69.5
February	8.72	90.5
March	12.63	102.5
April	5.39	51.0
May	1.84	17.0
June	1.47	0.0
July	0.84	1.0
TOTAL	88.72	620.0

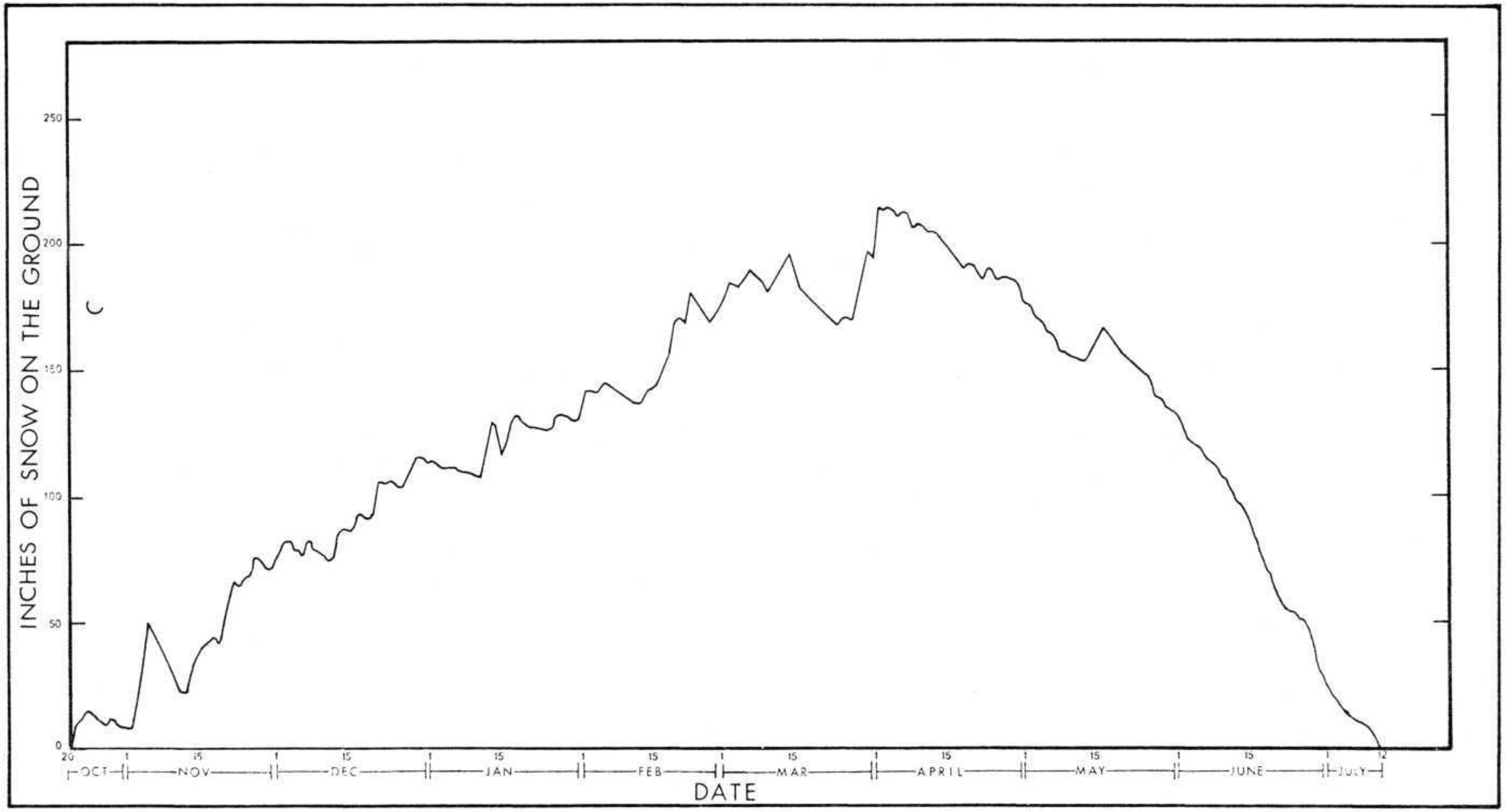


Figure 4: 1973-1974 Snow Accumulation at Park Headquarters, 6475 feet, Crater Lake National Park, Oregon

TABLE 2--MONTHLY TEMPERATURES: MEANS AND EXTREMES RECORDED AT PARK HEADQUARTERS FOR THE WINTER OF 1973-1974

MONTH	MEAN TEMPERATURES °F		EXTREME TEMPERATURES	
	Ave. Max	Ave. Min	Maximum	Minimum
October	50.0	28.0	68.0	18.0
November	30.7	21.8	41.0	9.0
December	31.9	26.3	43.0	46.0
January	29.6	13.2	45.0	-6.0
February	32.5	13.8	49.0	1.0
March	35.0	19.0	49.0	-7.0
April	36.7	18.6	57.0	9.0
May	46.9	25.8	61.0	27.0
June	61.1	35.3	73.0	21.0
July	65.0	39.0	80.0	30.0

III. FACTORS AFFECTING SNOW PACK DEPLETION

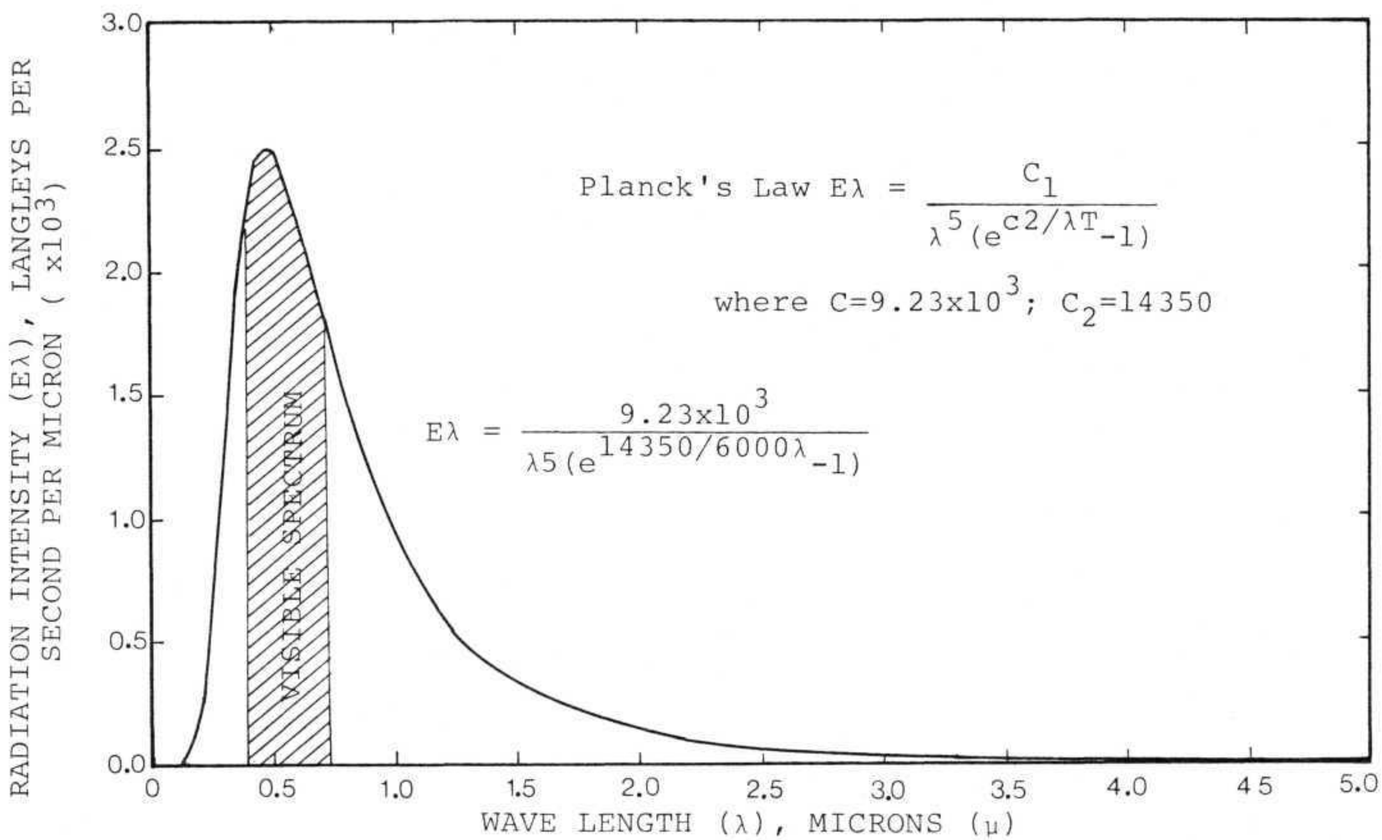
Fluxes of Heat Energy

Snow pack depletion is essentially a response to thermodynamic processes. The net heat exchange between the snow pack and its environment influences the quantity of snow that is ablated. The rate of ablation is directly related to the principle fluxes of heat energy and the condition of the snow pack.

The principle fluxes of heat energy which influence snow pack depletion include: 1) solar and terrestrial radiation, 2) sensible heat, 3) latent heat of vaporization, 4) conduction of heat from the ground and 5) heat content of rain water. These energy exchanges interact to affect the diurnal rate and quantity of snow pack depletion. (This information is a synopsis of materials presented by the U.S. Army Corps of Engineers, Snow Hydrology, chapters 5 and 6, pp. 141-258, 1956.)

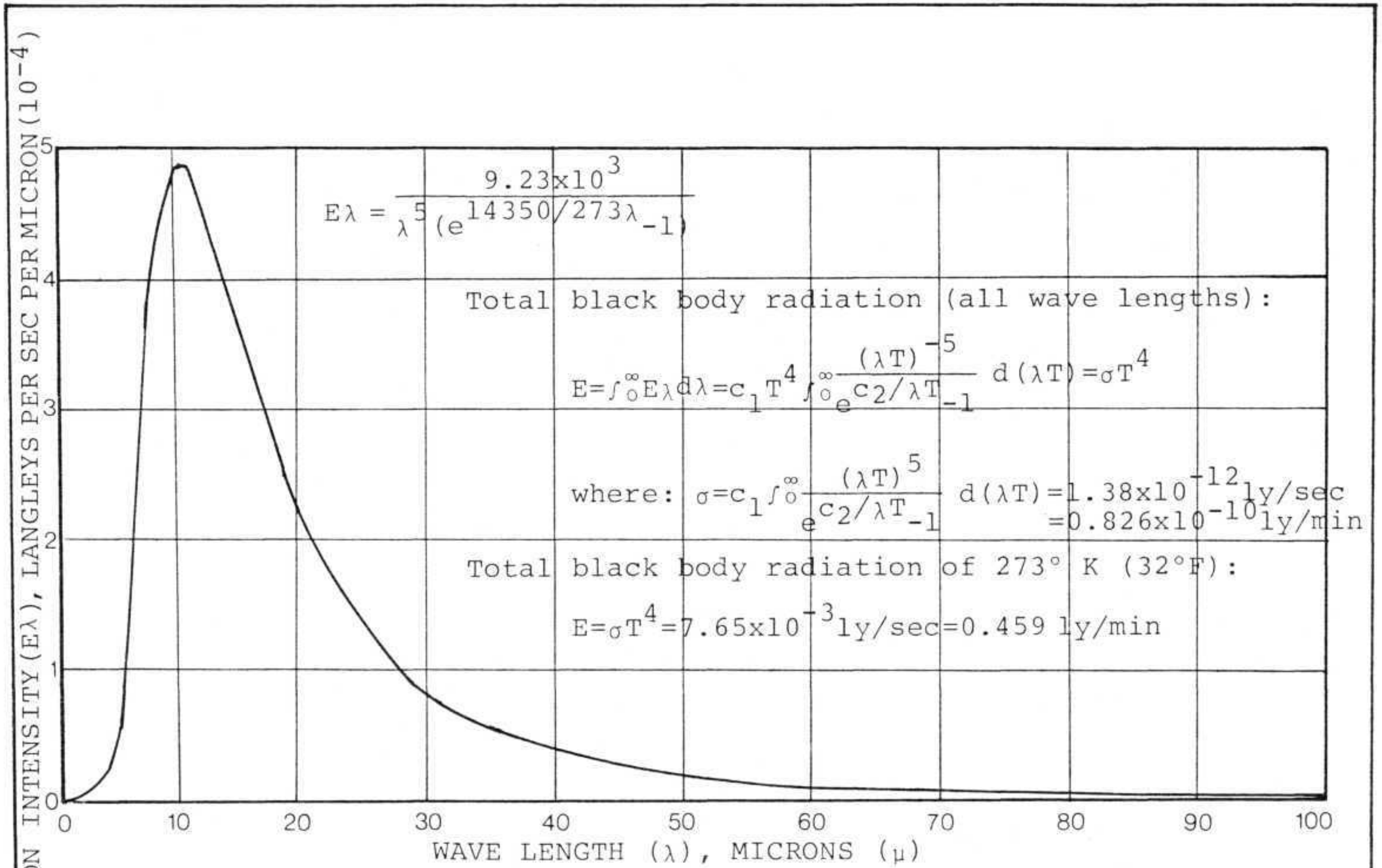
1. Solar and Terrestrial Radiation

Incoming solar (shortwave) and terrestrial (longwave) radiation influencing snow pack ablation comprises only a small portion of the entire electromagnetic light spectrum. Solar radiation ranges from 0.15 to 4μ, reaching a maximum intensity at .5μ and ranging in the visible spectrum from .4 to .7μ (figure 5). Terrestrial radiation encompasses the wavelengths of 3μ to 80μ reaching maximum intensity in the infrared at 11μ (figure 6) at average Earth surface temperatures.



SPECTRAL DISTRIBUTION OF RADIATION INTENSITY
FOR A BLACK BODY AT A TEMPERATURE OF 6,000° K.
(Theoretical Radiation Emitted by the Sun)

Figure 5: (U.S. Army Corps of Engineers, Chapter 5, plate 5-1, figure 2, 1956)



SPECTRAL DISTRIBUTION OF RADIATION INTENSITY FOR A BLACK BODY AT A TEMPERATURE OF 273°K (23°F) (THEORETICAL RADIATION EMITTED BY MELTING SNOW)

Figure 6: (U.S. Army Corps of Engineers, Chapter 5, plate 5-3, figure 1, 1956)

3. Stefan-Boltzmann Law: by means of integrating Planck's Law, the total energy emitted in all wavelengths from the snow pack can be determined. Hence, $E = \sigma T^4$ where:

E = total radiative power emitted at all wavelengths from the snow pack

T = temperature

and where:

$$\sigma = \int_0^\infty \frac{c_1}{(\lambda T)^5 (e^{c_2/\lambda T} - 1)} \, d(\lambda T)$$

$$(\sigma = 0.826 \times 10^{-10} \text{ langleys/minute/}(^\circ K)^{-4}$$

Solar radiation influences snow pack depletion because it affects the environmental microclimate above the snow pack. The daily insolation absorbed by the snow pack affects the rate of ablation. Factors which influence the quantity of insolation absorbed by the snow pack include atmospheric conditions, slope aspects, forest cover, albedo and the angle of incidence of the sun's rays.

The transparency of the atmosphere and the optics of the air mass affects the total portion of insolation the surface of the earth receives. Some light rays which penetrate the outer parts of the atmosphere never reach the earth's surface because of reflectance, absorption or scattering of the insolation. Clouds are the greatest hindrance to insolation penetration. However, some insolation

The general radiation theories apply to the snow pack since all bodies radiate energy. Both the spectral distribution and the intensity of the back radiation are directly proportional to the temperature of the snow pack. Specifically, the higher the temperature, the greater the intensity of the total radiation which is emitted from the snow. Since snow is considered a near perfect black body the following radiation theories are applicable:

1. Planck's Law: gives the spectral distribution of energy for a radiating black body.

$$E\lambda = \frac{c_1}{\lambda 5 (e^{c2/\lambda T} - 1)}$$

   E = intensity of the emitted radiation for wavelength

   T = temperature of the radiating body

   C = constants

2. Wien's Law: using Planck's Law, wavelengths of maximum radiation intensity can be determined. For any given temperature $E\lambda = 0$, when $\lambda = 0$ and $\lambda = \infty$; for an intermediate value of λ, $E\lambda$ = maximum value which can be derived from Planck's Law. Through differentiating and equating the zero Wien's Law is mathematically represented as:

$$\lambda m T = \text{Constant}$$

   λm = wavelength (in microns) at which E is a maximum

   T = temperature of the radiating body

eventually reaches the earth's surface. Generally, because of greater atmospheric transmission at higher elevations, more solar radiation is available for melting the snow pack in mountainous regions.

The slope aspect is of prime importance regarding snow pack depletion. In the northern hemisphere the radiation incidence is far more efficient on south facing slopes compared to those which face north. During the daily progression of the sun, the angle of incidence on the exposed slopes changes. The net result produces snow melt patterns related to these differences in the angle of incidence.

Insolation is also intercepted by the forest canopy. Characteristics such as forest density, tree species and canopy condition influences the amount of solar radiation available to ablate the snow pack.

Snow pack depletion is also affected by characteristics of the snow pack. The ability of the snow pack to reflect solar radiation depends upon the condition of the surface layers. The intensity of the albedo is independent of the angle of incidence. Generally, fresh fallen snow has an albedo of 80 percent decreasing exponentially to 40 percent for melting late season snow (figure 7).[4]

Thus, through an analysis of the various factors which influence the available solar insolation, snow melt components can be calculated. Snow depletion by solar radiation can be expressed as:

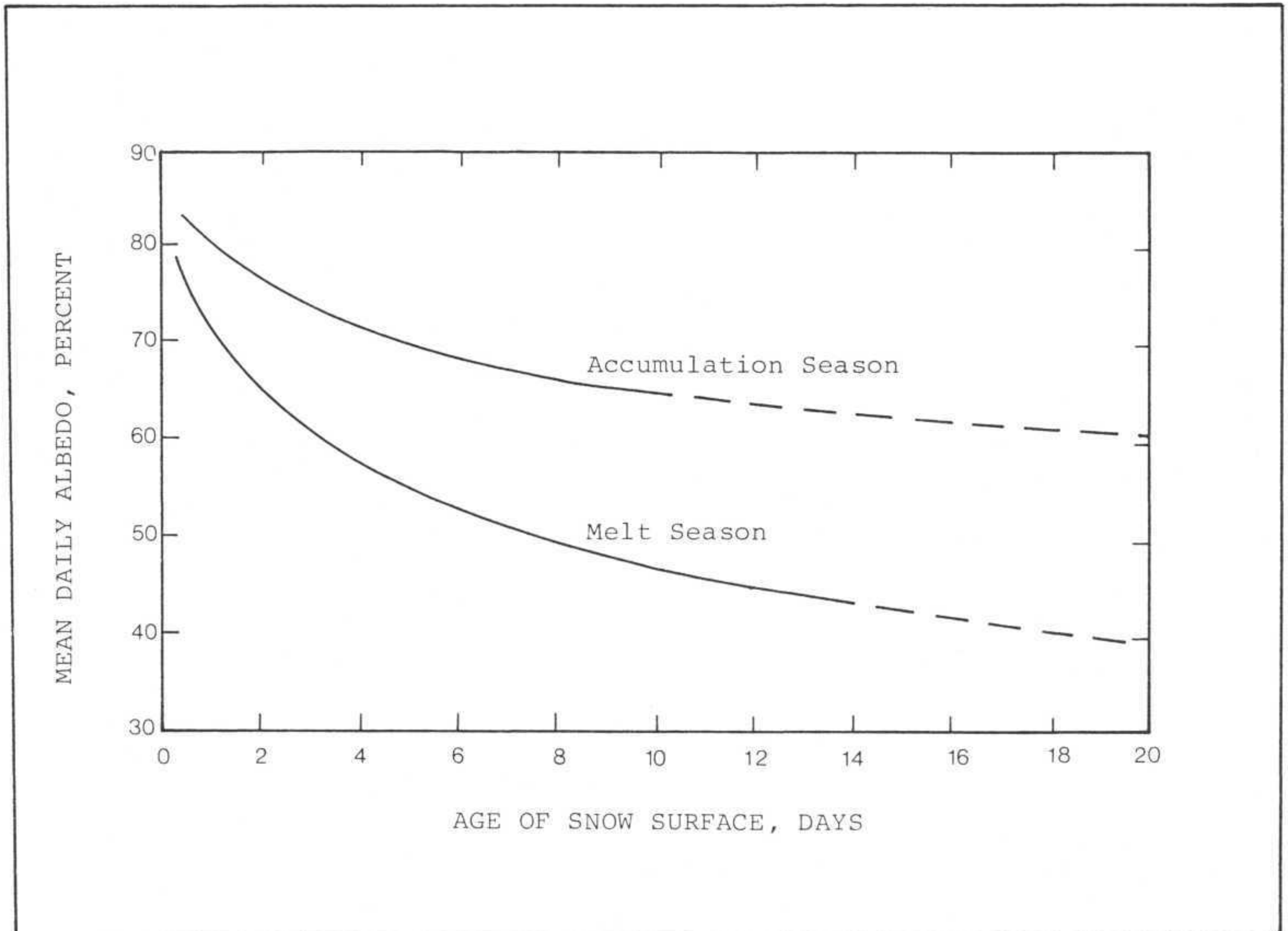


Figure 7: (U.S. Army Corps of Engineers, chapter 5, plate 5-2, figure 4, 1956)

$$Mrs = \frac{(1-a)Rsi}{203B} = 0.00508\ Rsi\ (1-a)\ \text{inches/day}$$

Mrs = Snow depletion by solar radiation

a = albedo written as a decimal fraction

Rsi = effective solar radiation in langleys/day

B = assumed to be 0.97 for a melting snow pack

Snow is regarded as a near perfect black body in respect to terrestrial (longwave) radiation. In accordance with Kirchhoff's Law, $e_B = a_B$ where: e_B = emissivity of a black body and a_B = absorptivity of a black body, the snow pack absorbs, at a given wavelength and temperature, all possible longwave radiation and emits the same amount of such radiation at the same wavelength and temperature. This process allows the amount of emitted radiation by the snow pack to be readily calculated. The intensity of emitted black body radiation can then be plotted for various temperatures (figure 8). Notice that the maximum amount of black body radiation is 0.459 langleys/minute since the maximum temperature of the snow pack is 32° Fahrenheit.

The amount of back radiation available is an integrated result of three factors: 1) the atmospheric condition, 2) clouds, and 3) forest cover. First, atmospheric moisture content and air temperatures determine the quantity of back radiation available to the snow pack. Both the moisture content and the temperature of the air mass determine how much back radiation is possible under clear skys. Second,

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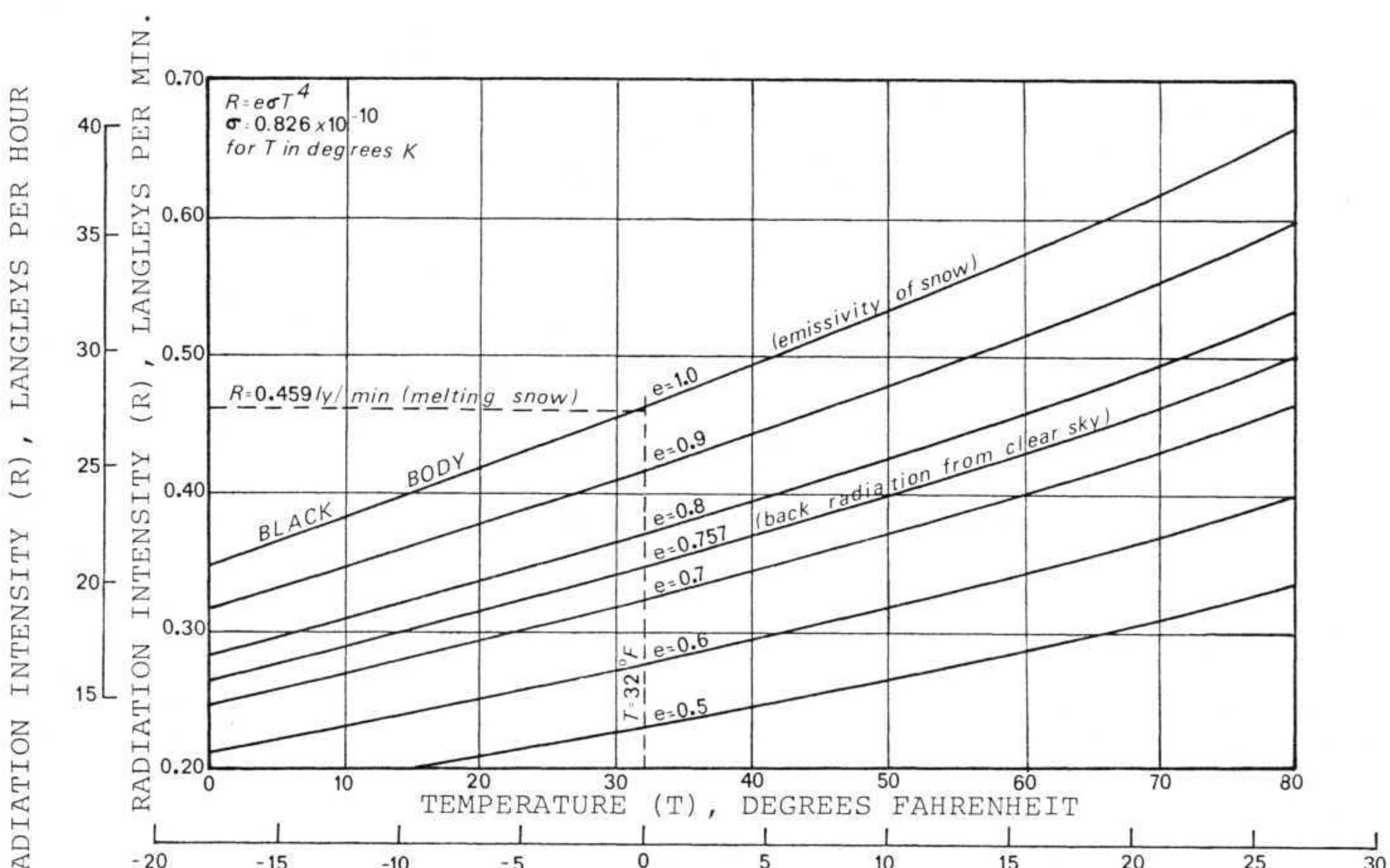


LONG-WAVE RADIATION EMITTED IN ACCORDANCE WITH THE STEFAN-BOLTZMANN LAW (FOR VARIOUS EMISSIVITIES)

Figure 8: (U.S. Army Corps of Engineers, plate 5-3, chapter 5, figure 2, 1956)

because clouds have a dominant effect on longwave radiation, the maximum radiation exchange between the clouds and the snow pack may be regarded as the net longwave radiation exchange between the two bodies where temperatures correspond to the snow and cloud base temperatures. That is:

$$R = \sigma (Tc^4 - Ts^4)$$

where:

R = net longwave radiation

Tc = cloud base temperature

Ts = snow surface temperature

Longwave radiation loss from the snow pack is greatest during periods of sparse cloud cover. Finally, radiation from the forest canopy is somewhat similar to the radiation from clouds since a tree canopy acts as a black body which absorbs and emits all possible radiation. The leaves which face the snow pack have temperatures which are approximately the same as the ambient air temperatures. Thus, the longwave radiation heat exchange between the snow pack and the forest canopy can be expressed as:

$$Rf = \sigma (Ta^4 - Ts^4)$$

where:

Rf = net longwave radiation heat exchange between a solid forest canopy and the snow pack

Ta = air surface temperature

Ts = snow surface temperature

In dense forest these relationships between the snow pack and the forest become more complex. Also, the species of tree and canopy condition affect the relationship between terrestrial radiation and the snow pack.

2. Convective Heat Transfer and the Latent Heat of Vaporization

The influence of convective heat transfer is of secondary importance to snow pack depletion. Turbulent air exchange over the snow covered area transfers heat and moisture to the snow surface releasing the latent heat of vaporization. Conversely, upward gradients of temperature and vapor pressure reverse this process.

Computations can be made to determine quantitatively the heat transfer flow and the rate of ablation produced by condensation heat transfer. That is:

$$Me = 0.054\ (ZaZb)^{-1/6}\ (e_a - e_o)\ ub$$

where:

Me = snow melt in inches/day

Za and Zb = heights of measurement in feet of the vapor pressure and the speed of the wind above the snow pack

e_a = vapor pressure in mb

e_o = snow surface vapor pressure in mb

ub = wind speed (m.p.h.)

Heat transfer from the advection of warm air over the snow pack is the primary cause of snow ablation in the convective heat transfer process. Factors which influence the depletion of the snow pack by convection include: 1) temperature gradient, 2) wind speed, and 3) air density (used as a function of air pressure). The effects of convection on the snow pack can be mathematically expressed as:

$$Mc = 0.00629\ (p/p_o)\ (ZaZb)^{-1/6}\ (Ta - To)\ ub$$

where:

Mc - snow melt (inches/day)

p = air pressure at the site

p_o = air pressure at sea level

Za = feet above snow pack of air temperature

Zb = feet above snow pack of wind speed

Ta = air surface temperatures in °F

To = snow surface temperatures in °F (snow surface normally measured at 32°F).

ub = mean wind speed (m.p.h.) at 50 foot level

The influence of convection and condensation on the snow pack can be calculated in one single equation for hydrological purposes. That is:

$$Mce = 0.0084\ [0.22\ (Ta - 32) + 0.78\ (Td - 32)]\ ub$$

where:

Mce = total condensation-convection melt in inches/day

Ta and Td = mean air and dewpoint temperatures at ten feet in height

ub = mean wind speed (m.p.h.) at 50 foot level

The results of these calculations can then be applied to formulate a graph illustrating the influence of condensation/ convection on the snow pack melt rates (figure 9).

3. Conduction of Heat from the Ground

Conduction of heat from the ground does not have a major influence on ablation when considered in daily computations. It has been predicted that a miminal value of 0.02 inches of snow/day ablate by heat conduction from the ground surface.[4] However, the impetus from ground heat is significant when it is considered for the entire snow pack depletion budget. This melt process has hydrologic ramifications because the ground, as a heat source, produces ablation during the winter and early spring when surface melt is practically nil. During these months, heat, which is stored in the ground during the summer and early fall, is transferred to the snow pack. The amount of heat which can be stored is dependent upon the thermal gradient and the conductivity of the ground, itself.

4. Heat Content of Rain

Snow pack ablation is also influenced by rain which falls directly onto the snow surface. The rain is cooled to the temperature of the snow thereby transferring heat to the snow pack. The amount of heat surrendered to the snow by the rain is directly proportional to the quantity of rainfall and the temperature excess of the rain water above the temperature of the snow pack (figure 10). If

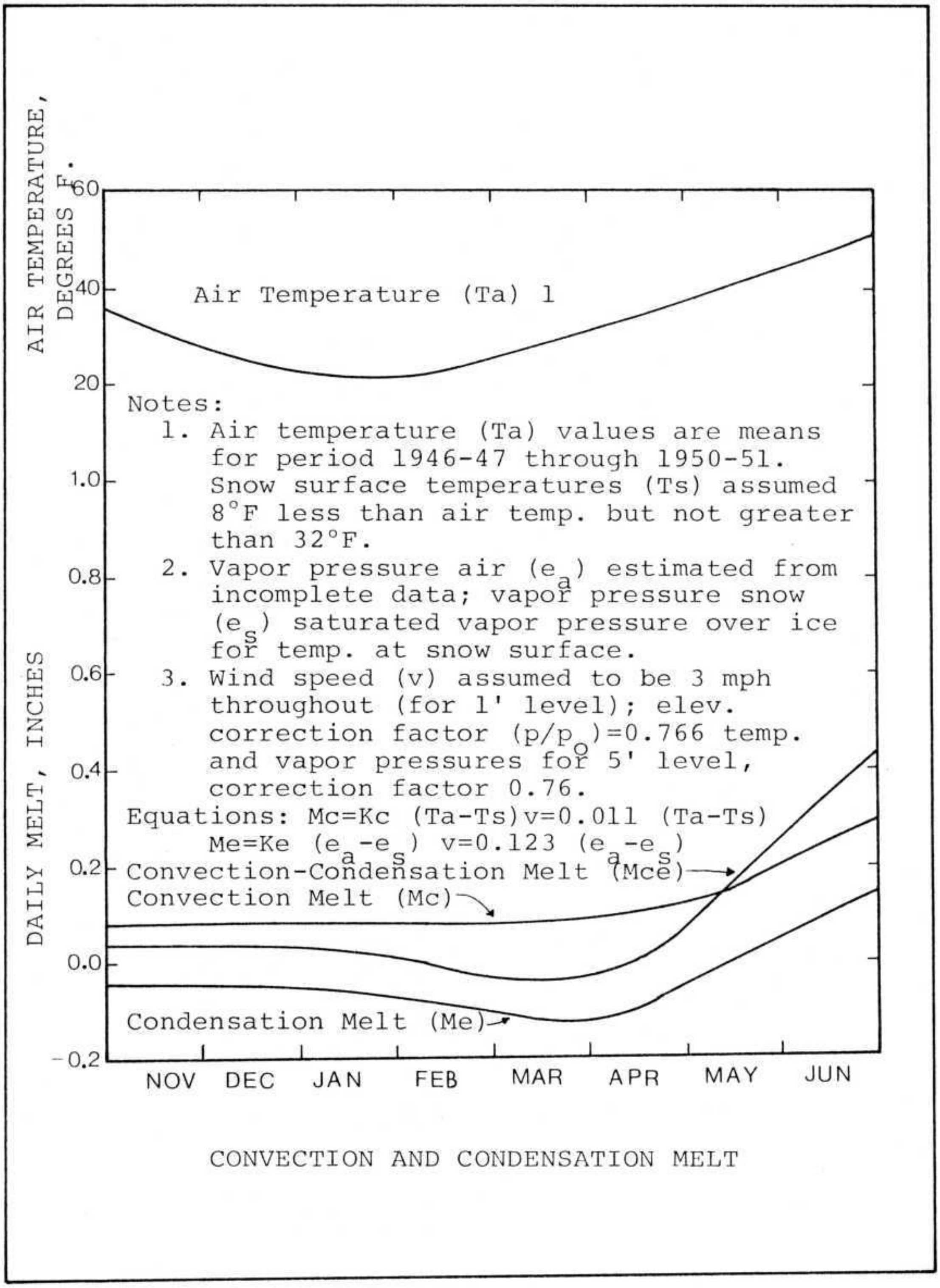


Figure 9: (Source: U.S. Army Corps of Engineers, chapter 5, plate 5-7, figure 3, 1956)

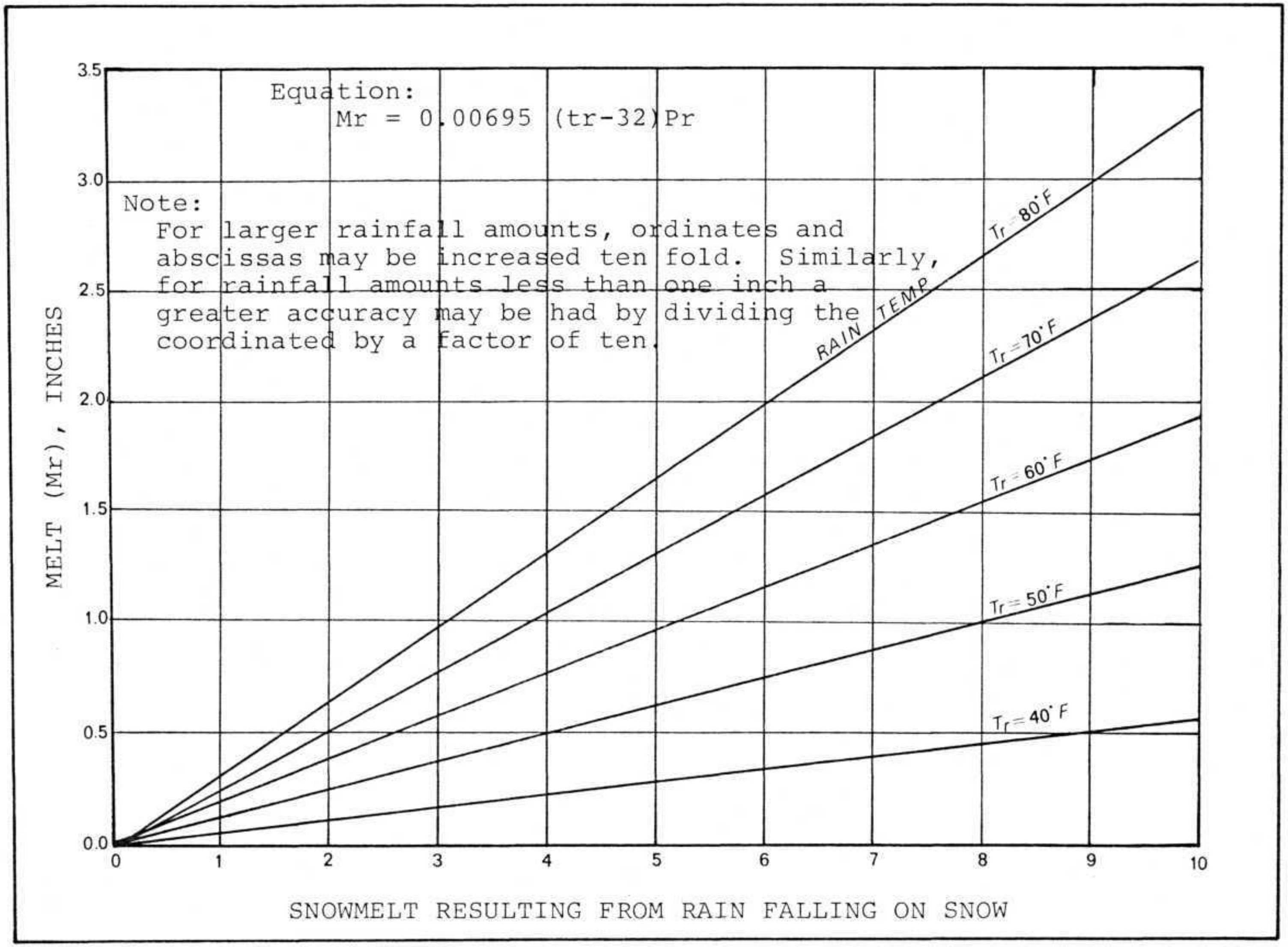


Figure 10: (Source: U.S. Army Corps of Engineers, chapter 5, plate 5-6, figure 2, 1956)

the rain water is eventually frozen within the pack greater amounts of energy are distributed to the snow field because the latent heat of fusion is released by the rainwater. Hence, snow packs which prevail during periods of intense rainstorms cannot develop to any considerable magnitude.

Energy Budget Equation

Energy budget equations can be formulated and snowmelt summary graphs can be constructed through the consideration of the various principle fluxes of heat energy (figure 11). If all heat fluxes directed toward the snow pack are regarded as a positive input and those away from the pack negative, then the summation of both of these heat transfer processes is zero (when snowmelt is considered as another heat transfer process and including the changes which occur in the thermal quality of the snow itself).

$$\Sigma H = Hrs + Hrl + He + Hc + Hg + Hp + Hq + Hm = 0$$

where:

ΣH = algebraic sum of all heat contributions (cal/cm^2)

Hrs - absorbed solar radiation

Hrl = net longwave radiation exchange between the snow pack and its environment

He = latent heat of vaporization released by condensate

Hc = convective heat transfer (sensible heat) from the air

Hg = conduction of heat from the ground

Hp = heat content of rain water

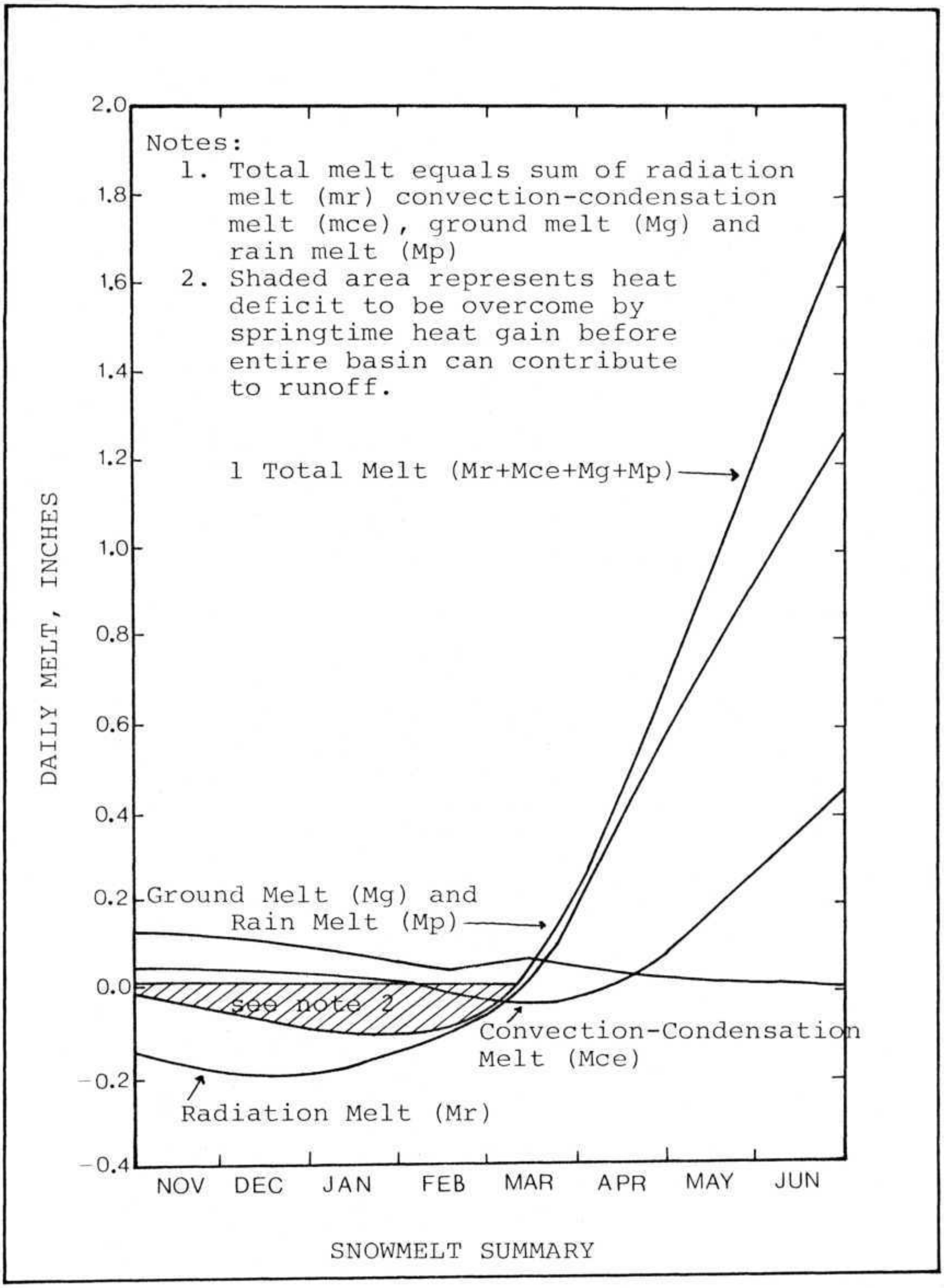


Figure 11: (Source: U.S. Army Corps of Engineers, chapter 5, plate 5-7, figure 5, 1956)

Hq = change in energy content of the snow pack

Hm = heat equivalent of the snowmelt

Inferring from the above equation it follows that melt can be expressed as:

Hm = Hrs + Hrl + He + Hc + Hg + Hp + Hq

when:

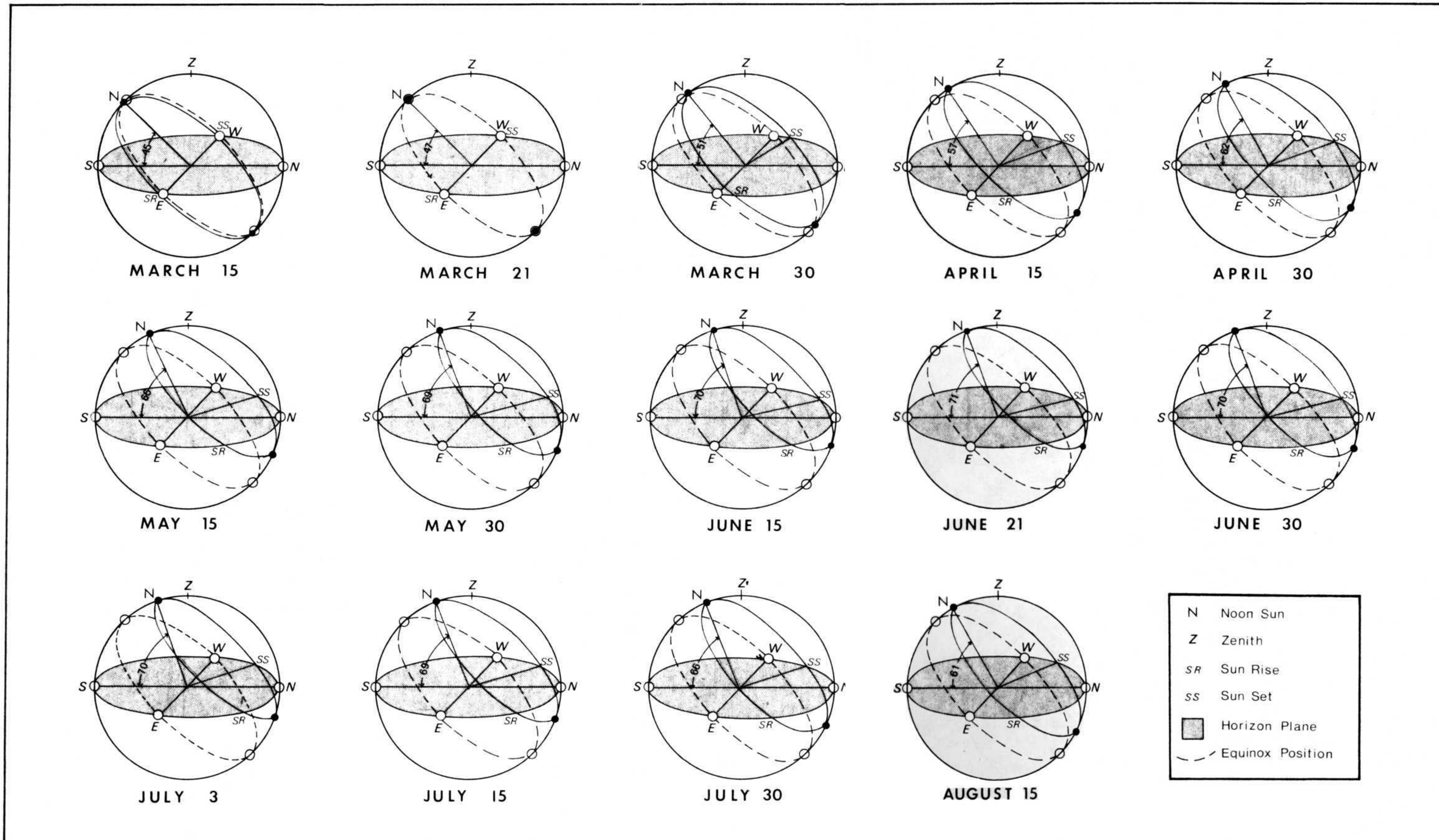
1) the heat equivalent of the melt is positive
2) Hrl = ordinarily negative in the open
3) He and Hq = either positive or negative
4) He = generally positive
5) other terms in the equation are always positive

Earth-Sun Geometry Affecting Snow Melt at Crater Lake

The rotation and revolution of the earth, combined with the inclination and polarity of the earth's axis are factors which influence the angle of incidence of insolation. Associated with these occurrences are variations in the effectiveness of solar insolation due to changes in the transparency of the atmosphere. All of these factors directly influence the quantity and rate of snow pack depletion.

The earth-sun geometry at Crater Lake (latitude 42°56'N) influences the ablation of the snow pack. Each year the sun's apparent path over the study area from spring until mid-summer increases in angle from 45 degrees to a maximum of 71 degrees above the horizon (figure 12). Just prior to the vernal equinox (March 21) the sun rises at a point just south of east and sets at a location just south of west.

Figure 12: Apparent Path and Inclination of the Sun over Crater Lake (latitude 42° 56' N) from March 15 through August 15, 1974.



During this period of time the inclined light rays penetrate the atmosphere and diffuse the energy over the ground surface.

Following the equinox the path of the sun then begins to rise north of east and set north of west on the horizon. As the sun achieves greater angles above the horizon less light diffusion on the ground surface occurs due to changes in the transparency of the atmosphere and because the rays are closer to a perpendicular angle with the horizon. Associated with this phenomenon are longer periods of light and more intense sun rays. However, following the summer solstice (June 21), the sun angles begin to lessen in response to the changing earth-sun relationships.

In the study area three locations provide good examples of how the earth-sun geometry influences snow depletion. These areas are, 1) Wizard Island, 2) the caldera and 3) Chaski Slide.

Wizard Island is a symmetrical cinder cone located inside the caldera. As would be expected, ablation is most noticable on the southern exposures of the island. The angle of incidence during the late spring on Wizard Island is considerably lower during this part of the year. The sun's rays strike the south eastern facing lower slopes depleting the accumulated snowfield. With time, as the angle of incidence increases, a noticable shift in ablation occurs on the entire south facing slope ablating the snow pack in the steeper areas. Eventually, as the sun reaches its greatest angle above the horizon the upper south western facing slopes are depleted.

The caldera walls also display melt characteristics related to earth-sun geometry. The southern exposures of the caldera receive direct sunlight most of the year creating an area whereby ablation exceeds accumulation.

The eastern facing caldera walls receive varied amounts of direct insolation in response to increasing sun angles. During the equinox, the sun's rays strike the north eastern facing walls of the caldera. The snow begins to ablate producing a broken snowfield with sporadic patches of snow. As the sun angle increases, the direct light rays encounter the south eastern facing walls closer to the rim of the caldera. The direct lighting of this portion of the caldera does not last long enough to completely ablate the snowfield but rather produces a highly complex pattern of snow patches. The toe of the caldera in this location receives little direct sunlight because of the caldera's steepness. The net result produces large sheltered snow patches which slowly melt throughout the summer.

One critical snow accumulation zone located on the northern facing slopes of the caldera is Chaski Slide. This area is a land slump which is sheltered on three sides by steep escarpments combined with promontories which protrude beyond the slide in a northerly direction. During most periods of the year this area is completely devoid of intense sunlight because of the shadows cast by the escarpments and promontories. Only the lower portions receive direct sunlight producing snow pack depletion in this area. However, since direct sunlight does not strike most of Chaski Slide a large snowfield is able to be maintained most of the year. There is one patch of snow which characteristically doesn't melt during the year; that patch of snow has existed there longer than a decade.

IV. METHODOLOGY FOR DETERMINING SNOW COVER

High flight aerial (U-2) photographs and ERTS-1 multispectral images were utilized throughout this research. The procedure followed a systematic approach examining first the snow extent on the high flight photographs. The results from these examinations were directly applied to the satellite images. Evaluations were then made to determine the potential applications of ERTS-1 multispectral photographs for snow line delineation and the utility these images provide to the field of snow hydrology.

Aerial Photographs

On July 3, 1974, high flight aerial color infrared photographs were taken over Crater Lake National Park (flight number 74-115). The study area was photographed at an altitude of 65,000 feet using two basic formats: a 9" x 9" (scale = 1:130,000) image (camera focal length - 6") and a 9" x 18" (scale = 1:30,000) frame (camera focal length - 24"). These photographs were made available for research analysis by the Environmental Remote Sensing Applications Laboratory (ERSAL) located on the Oregon State University campus. Both sets of images were utilized throughout this research to provide and establish a basis of "ground truth" for the study area.

A black and white red sensitive emulsion was used to produce negatives and prints from the high flight color infrared transparencies. The utilization of the black and white photographs was necessitated by cost factors and by the greater advantages and versatility that the black and white prints afforded.

It was determined that color infrared transparencies made detailed snow analysis difficult. The sharp definition between minute snow/no snow boundaries could not be accurately delineated because of hue variations on the color print. Many times the color transparencies produced a "saturated" image creating a false snow cover in critical localities resulting from excessive reflectivity from the snowfield and adjacent pumice slopes.

These critical variations in color were not present on the black and white images. The black and white photographs provided sharp, well defined snow boundaries at a reasonable cost. In addition, enlargement or reduction of the original black and white photography was easily accomplished to maintain a standard scale (1:130,000) for the 9" x 9" photographs, ERTS-1 images and the snow extent map of Crater Lake.

The snow extent within the study area was determined by using stereo coverage of the 9" x 18" black and white infrared photographs. These photographs offered high resolution at a good scale (1:30,000). This permitted the snow cover to be mapped with extreme accuracy.

The snow line delineation was accomplished using a Abrams Model CB-1 four power stereoscope. The magnification produced by this stereoscope allowed the smallest patches of snow to be mapped. The snow extent was identified and mapped at the edge of the outer snow limit. This critical zone was easily delineated throughout the study area. All isolated patches of snow outside the snow boundary, regardless of size, were accounted for and mapped accordingly. Likewise, all areas devoid of snow within the snow cover were mapped. The results of this detailed mapping produced small snow extent overlay maps for the local which they represented (figure 13).

A photo-mosaic was then constructed for the entire study area after the analysis and mapping procedure was completed from each stereo pair of 9" x 18" photographs. The specific photographs utilized during the snow map compilation procedure was incorporated in the photo-mosaic. Each photograph in the mosaic was visually aligned with the adjacent photographs. Rectification of the images was not attempted because of cost/time elements. Small changes in scale occur between the photograph boundaries due to the pitch and roll of the airplane in the turbulent air currents above Crater Lake. However, since most scale changes are minute, they are difficult to discern.

Using the photo-mosaic, a snow extent mosaic was assembled for the complete study area. The snow cover overlays were positioned onto the specific photograph from which they were mapped. A large piece of clear acetate

Figure 13: Snow extent overlay map for the Wizard Island local.

was then placed directly over both the photographs and the snow delineation overlays. The areas devoid of snow were designated black in color and those with snow were left white. The final map clearly and accurately delineates the margins of the snow cover, small isolated patches of snow, snow melt characteristics and the effects of changes in altitude, slope aspect, and earth-sun relationships throughout the study area. The snow-mosaic map was then reduced to approximate the scale (1:130,000) of the 9" x 9" high flight aerial photographs (figure 14, the original 1:30,000 snow-mosaic map is provided in the envelope on the back cover of this thesis).

ERTS-1 Coverage

An accurate evaluation of ERTS-1 imagery was dependent upon synchronous photographic coverage of the study area with both the satellite imagery and the high flight aerial photographs. June 30, 1974, was the date of the ERTS-1 over flight above Crater Lake that most nearly coincided with the July 3 date of the high flight aerial coverage. There is good agreement between the satellite images and the U-2 photographs regarding the snow extent in the study area.

Since the ERTS-1 satellite is equipped with a multispectral scanner the snow cover at Crater Lake was recorded in four distinct wavelength bands (MSS-4, 5, 6, and 7) including near infrared (see Appendix A for details of the ERTS-1 system). The appearance of the snow on each of

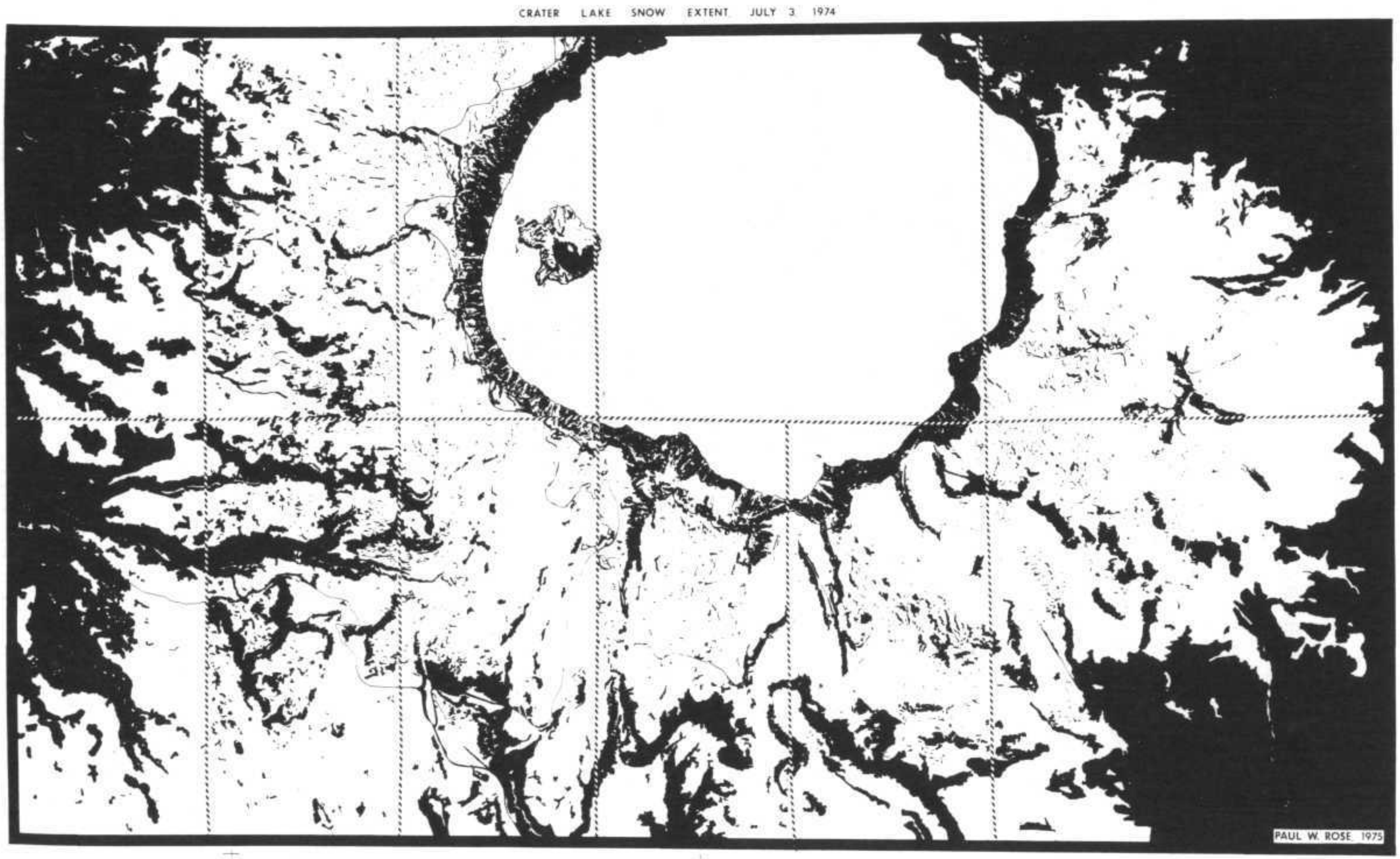


Figure 14: Snow-Mosaic Map of Crater Lake National Park, Oregon (the white area indicates the snow limit; dark areas represent areas with no snow; stripped lines indicate the boundaries of the unrectified photographs)

these distinct bands was considered in the final evaluation of ERTS-1 imagery as a tool for potential hydrologic application.

The original ERTS-1 photographs were at a scale which was unsuitable for hydrologic purposes (1:1,000,000). In order to facilitate an accurate evaluation of the ERTS-1 multispectral bands the small scale originals were enlarged to equal the scale of the 9" x 9" high flight photographs (scale = 1:130,000). At this scale a great amount of detail could be discerned from the ERTS-1 imagery. However, the enlarged ERTS-1 photographs could not accommodate increased large scale adjustments because of the tremendous decrease in resolution.

Snow lines were delineated on the ERTS-1 images utilizing a zoom transfer scope. This procedure allowed the snow-mosaic map to be superimposed onto the ERTS-1 photographs at the same scale (1:130,000) providing optimum detail of the snow cover. This process was necessitated by the scale changes within the snow-mosaic map of Crater Lake produced by parallax problems in areas of varied topography. The manipulation of the superimposed ERTS-1 images onto the snow mosaic map using the zoom transfer scope counteracted most of the parallax problems. Where the major parallax difficulties could not be compensated for due to numerous topographical relief changes, the snow line had to be visually adjusted using changes in the gray scale density in the snow covered area.

Only the critical snow covered areas were mapped using this process. The snow-mosaic map served as a function of "ground-truth" so that the snow cover in the study area could be readily mapped on the ERTS-1 images utilizing the zoom transfer scope. Hence, accurate snow cover maps were prepared to delineate the snow cover in the study area on the satellite photographs so that evaluations could be made regarding the application of ERTS-1 imagery to snow hydrology.

V. SIGNIFICANT RESULTS

ERTS-1 imagery has definite potential to the field of snow hydrology. The satellite photographs provide a basis for accurate and detailed analysis of the snow extent. Each band possesses its own unique characteristics which allows most facets of the snow cover to be examined. The significant results of this research includes the determination of appropriate scale utilization of ERTS-1 images for snow hydrology, an evaluation of each spectral band for delineating snow extent and an analysis of multispectral image manipulation to achieve accurate mapping of snow conditions for any study area.

Scale Utilization

Major researchers, including the United States Geological Survey, utilizing ERTS-1 imagery for snow cover delineation have indicated that a scale of 1:250,000 is the largest scale possible for accurate research analysis. This research has determined that this is simply not true for all situations. Throughout this research, the ERTS-1 images were utilized at a scale of 1:130,000, this scale provided the researcher with detailed photographs for snow analysis. Hence, accurate and detailed snow extent maps were prepared from ERTS-1 imagery using a scale of 1:130,000.

It can be argued that scale adjustments larger than 1:250,000 render resolution too poor for accurate evaluation using ERTS-1 images. It is true that resolution decreases as the scale is enlarged, however, at a scale of 1:130,000 ample resolution is maintained to provide adequate data from the ERTS-1 imagery. Additional large scale adjustments above a scale of 1:130,000 are not recommended because accurate evaluations of the satellite photographs would be hindered by the decrease in resolution.

Evaluation of ERTS-1 Imagery - Band by Band

The ERTS-1 imagery band in which snow has been most frequently identified in previous studies is the MSS-5 (0.6 to 0.7μm). The MSS-4 band (0.5 to 0.6μm) has also been used on occasion. Both bands seem to have provided a good snow image because snow has a greater reflectance than the surrounding snow-free terrain. However, the MSS-5 band is the one which seems most used for snow hydrology.

Greater difficulty in detecting snow on ERTS-1 images occurs with the images constructed in the longer wavelengths of reflected solar radiation. It has proved to be more difficult to map snow-cover using the MSS-6 (0.7 to 0.8μm) and MSS-7 (0.8 to 1.1μm) bands because snow is less reflective in the longer wavelengths. Even though the snow is less reflective, the near-infrared MSS-7 band has been utilized by the snow hydrologist to detect melting snow.

The present study suggests that the combination of all four bands, in a specific sequence, is necessary to extract maximum snow hydrologic information from the ERTS-1 imagery. A brief review of previous research efforts is delineated in the following chapter.

1. MSS-4 Image

The ERTS-1 image which intercepts and records the shortest wavelengths of visible light is band 4 (0.5 to 0.6μm). A good snow cover image is present on the band 4 photograph because snow has a greater reflectance than the surrounding snow-free terrain in the shorter wavelengths of light (figure 19). Most researchers tend to ignore this band for hydrological purposes. However, this research has determined that band 4 provides a greater amount of detail throughout the snow cover than has been previously accepted. This is especially true for snow extent delineation.

Band 4 does an excellent job delineating the outer extent of snow cover. Even though the image does appear saturated in areas of maximum snow cover this band provides ample halation contrasts to allow detailed snow cover mapping. The sharp break between the intermediate gray and the dark gray tones demarks the limit of maximum snow extent (area A, figure 20). Snow cover delineation should occur at this contact. In this study some delineation problems were encountered because of parallax differences between the U-2 and ERTS-1 imagery (area A_1, figure 20). The aerial photographs used to make the snow-mosaic map were not rectified, hence, parallax induced scale changes were apparent in the snow-mosaic map. Snow maps, which were prepared using the zoom transfer scope for the MSS-4 image were not accurate because of the inherent parallax problems with the snow-mosaic map. Better accuracy could be achieved through rectification procedures of the aerial photographs prior to the development of the snow-mosaic map.

Snow cover in areas of coniferous forest is also apparent on the MSS-4 image. The prime indication of this occurrence would be the changes in the gray scale within the established snow cover. The trees appear as an intermediate gray (area B, figure 20). The break in halation from a bright saturated image to an intermediate gray tone defines the snow cover which occurs in the forest area. However, the major limitation of this band for determining snow in trees is the fact that the researcher cannot differentiate snow in trees from rock outcroppings devoid of snow (based on gray scale changes). This problem can be counteracted by using other ERTS-1 bands for this purpose.

Open snow covered areas can be easily discerned from the ERTS-1, Band 4 image. These areas assume an appearance of a bright white in tone (area C, figure 20). However, because of the reflectance from the snow, the image appears saturated, hindering the amount of information that can be discerned regarding open, snowless zones in the snow covered areas. Other bands provide greater accuracy in interpreting these local conditions.

Band 4, then, does a poor job in delimiting rock outcroppings devoid of snow and areas of melting snow. The gray scale changes for open rocky areas cannot be discerned from other gray scale differences within the snow pack (area D, figure 20). However, band 4 does an excellent job of delineating open pumice areas outside of the snow extent. A sharp break from intermediate gray to dark gray occurs at the contact between pumice and forested areas respectively. It is inherent in the nature of band 4 to poorly indicate melting snow because this band intercepts only short wavelengths of light (area E, figure 20).

2. MSS-5 Image

The MSS-5 image (0.6 to 0.7μm) provides a good basis for delineating snow extent. The image is enhanced because, like band 4, the snow has a greater reflectance than the surrounding snow-free terrain. Due to the character of the wavelength of light it receives, band 5 also affords lesser detail in areas within the snowpack because the image tends to be saturated (figure 21).

Band 5, as well as band 4, does an excellent job defining the outer limit of the snow cover. The snow margins can be mapped on band 5 at the contact between the secondary grays and the intermediate grays (area A, figure 21). However, mapping procedures utilizing this critical contact zone between gray densities can be misleading. Some secondary gray scales indicate the presences of snow in areas where snow does not exist (area A_2, figure 21). This presents a serious problem to snow extent delineation using band 5. In addition, similar parallax problems encountered with band 4 were also present in delineating snow extent using band 5 (area A_1, figure 21). Therefore, accurate snow cover mapping cannot, independently, rely upon the image produced by band 5. This limitation can be compensated for through an analysis of the snow cover on the MSS-4 image. Band 4 can be used to develop the initial base map for the snow margins. Accuracy and detail could then be added to this base map through an analysis of the MSS-5 image.

The snow cover in coniferous forests is portrayed quite well on the band 5 image. This band does an excellent job delineating these areas. A secondary gray scale break occurs inside of the maximum snow cover to indicate the presence of snow in trees (area B, figure 21).

The MSS-5 image does a fair job in indicating open areas with snow. The image lacks detail, due to saturation caused by the reflection from the snow (area C, figure 21). Greater detail of snow in open areas can be obtained from the bands (MSS-6 and 7) in the longer wavelengths of reflected solar radiation.

The rock outcroppings devoid of snow are somewhat defined using band 5. There is a definite break in the gray scale where these areas are situated. However, the gray tone assumes the same secondary gray density as the area containing coniferous trees (area D, figure 21). Therefore, an accurate evaluation is hindered by this problem rendering the MSS-5 image less than suitable for delineating snow-free rock outcroppings.

The MSS-5 image does a poor job delimiting areas of melting snow. Because band 5 receives the wavelengths of red visible light, there is no indication of melting snow on the image (area E, figure 21).

3. MSS-6 Image

Because snow is less reflective in the longer wavelengths of reflected solar radiation greater difficulty arises in attempting to delineate the snow extent using band 6 (0.7 to 0.8μm) Hence, most researchers have not relied on the possibilities for snow cover evaluation provided by the MSS-6 image. Contrary to most opinions, this research has determined that band 6 is quite versatile, provides a significant amount of information and allows accurate evaluations of the snow cover to be formulated (figure 22).

The overall effectiveness of band 6 for delineating the maximum limits of the snowfield was difficult to determine. The parallax problems within the snow-mosaic map of Crater Lake hindered adequate evaluation. In the western half of the study area, where the changes in relief are critical, band 6 does not indicate (visually) defined breaks in the gray scale (area A_1, figure 22). However, in the eastern half of the study area where the terrain gently dips to the east there is close agreement with the actual snow boundary and the changes in the gray scale density (area A_3, figure 22). This break occurs between the secondary gray and the dark gray contact. Because of this close agreement, it can be assumed that band 6 could only be utilized in a tertiary capacity to evaluate the snow limit in critical areas.

Band 6 does a very good job indicating snow in trees. Intermediate grays within the saturated area as indicated on band 5 indicates the presence of snow in trees within the snow extent (area B, figure 22). However, the same density of gray is encountered outside of the snow boundary. Hence, the MSS-6 image should only be used to delimit snow in trees in this area after the maximum snow boundary has been established by use of bands 4 and 5.

The snow covered open areas can be discerned quite well using the MSS-6 image. The longer wavelengths of light recorded on band 6 gave the open, snow covered areas a very bright white tone (area C, figure 22).

The MSS-6 image does only a fair job in delineating areas of melting snow. Only the largest melting snow covered areas which are thin and nearly melted out register on the photograph (see small gray dot to the west of area E, figure 22). This could be expected as band 6 is not sensitive to the wavelengths which best indicate melting snow (i.e., those from 0.8 to 1.3μ).

Band 6 is excellent for defining snow-free rock outcroppings. This is a result of the lesser reflectivity of rock in these longer wavelengths. This darker grayness within the snow covered area emphasizes the snow-free rock surfaces. A definite break in the gray scale (dark gray) within the snow extent indicates the presence of these areas (area D, figure 22).

4. MSS-7 Image

The greatest difficulty in detecting the outer snow boundary, bare rocks in the snowfield, and trees with snow beneath them, is experienced with band 7. The MSS-7 band intercepts the longest possible wavelengths of reflected solar radiation for the ERTS-1 system (0.8 to 1.1μm). Even though the general characteristics of the snow cover are less discernable with this band, it does provide a great amount of information regarding deep snow packs and snow which is melting (figure 23).

The utilization of the MSS-7 image for delineating the snow extent, then, is very poor. This band is unsuitable for mapping the snow cover because the marginal area of the snow is not well defined by detectable gray scale changes (area A, figure 23). The marginal area with snow has the same light gray density as the forest without snow.

Band 7 is also unsuitable for the detection of snow in coniferous forests (area B, figure 23). The adequate halation to allow this boundary to be mapped just does not exist.

Band 7 does an excellent job defining open areas with snow. The MSS-7 band has a distinct bright white image in these areas (area C, figure 23). This characteristic allows accurate delineation of the greatest and deepest snow cover on the photograph.

The most outstanding characteristic of the MSS-7 image is its ability to detect melting snow. The spectral reflectance of melting snow greatly decreases in the near-infrared spectrum. This has been verified by research completed by the Cold Regions Research and Engineering Laboratories (CRREL, 1973) and Mantis (1951), (figure 15). Because of this decrease in reflectance, the MSS-7 band can be utilized by the snow hydrologist to detect melting snow.

An intermediate gray tone <u>within the established snow cover</u> indicates the presence of melting snow in this band (area E, figure 23). The basic limitation to the effectiveness of ERTS-1 imagery for detecting melting snow in the MSS-7 band is the fact that this band observes energy only to 1.1μm rather than to 1.3μm.

It is nearly impossible to discern rock outcroppings devoid of snow using the MSS-7 image. These snow free areas have a dark gray density which is similar to the density for forests with snow (area D, figure 23).

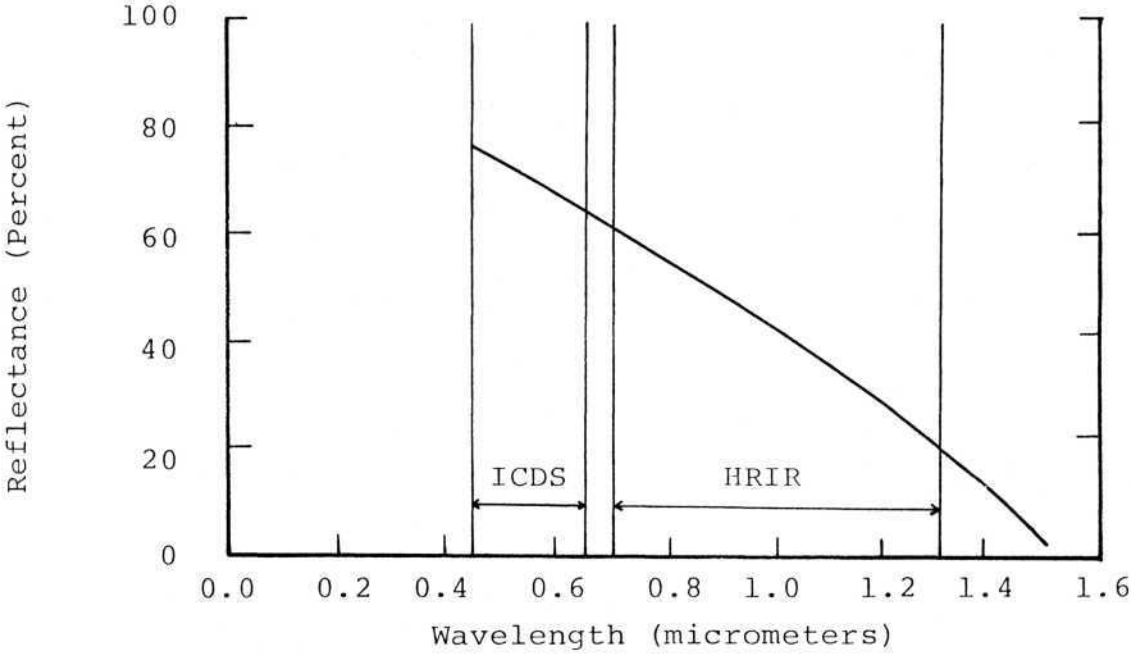


Figure 15: Spectral reflectance of melting snow (Source: Mantis, 1951, taken from Wiesnet, D.R., et.al., Reference 28, p. 1004, 1973)

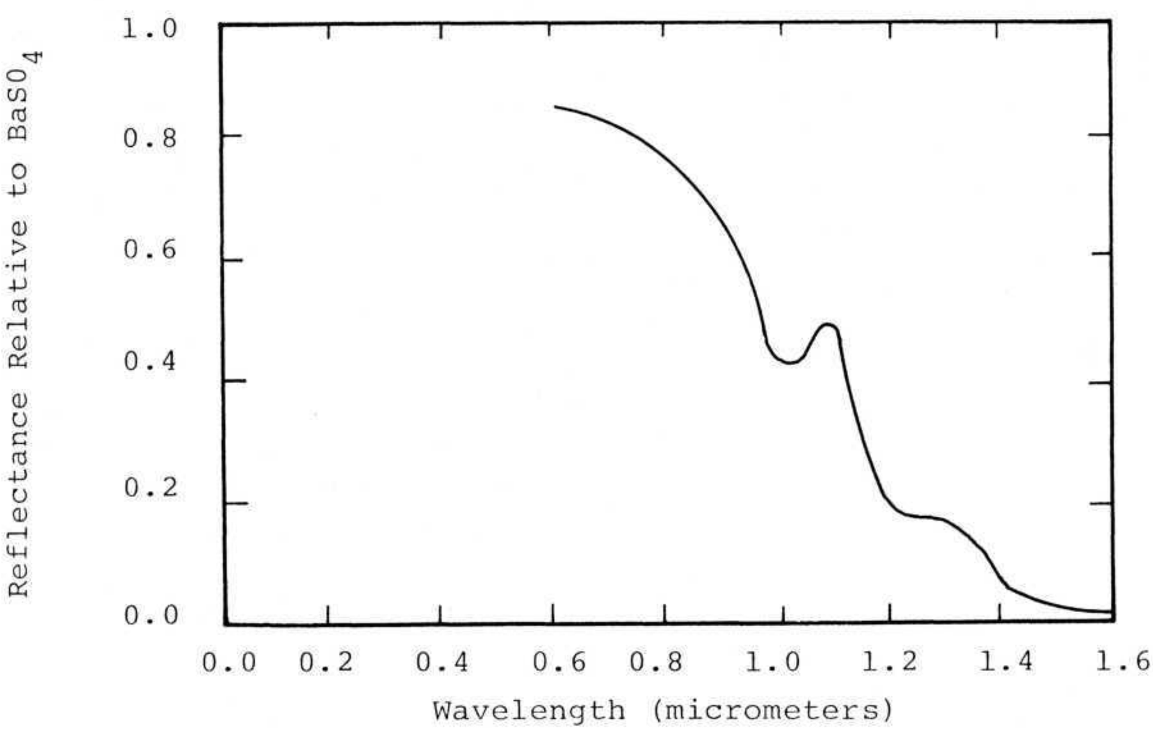


Figure 15(A): Spectral reflectance of melting snow at 0°C in cold room at CRREL (Source: taken from Wiesnet, D.R., et.al., Reference 28, p. 1004, 1973)

Multispectral Use of ERTS-1 Imagery for Mapping Snow Conditions

ERTS-1 imagery can provide data to the hydrologist on regional variations of the snow cover which can be utilized to monitor rapidly changing moisture conditions over large and remote areas. Each spectral band provides pertinent information on the snow conditions. As an isolated entity each image cannot provide adequate information to permit detailed snow cover evaluations. However, when all bands are analyzed for a given snow pack, accurate and detailed snow evaluations can be formulated.

A *flow chart* was prepared to develop a systematic process for snow pack evaluation utilizing ERTS-1 imagery (figure 16). In order to develop a detailed snow analysis for a study area each step must be completed. If an image does not apply to the particular category encountered then it can be simply discarded for that step. However, if the image can be utilized for the specific category being evaluated, then it must be considered in the order that it appears. By following the sequential steps indicated on the flow chart, a detailed and accurate snow analysis can be formulated.

The basis for a complete analysis of snow conditions on ERTS-1 imagery is the defining and mapping of the maximum snow extent. After the marginal limit of the snowfield has been determined the researcher can then deal with internal snowfield considerations.

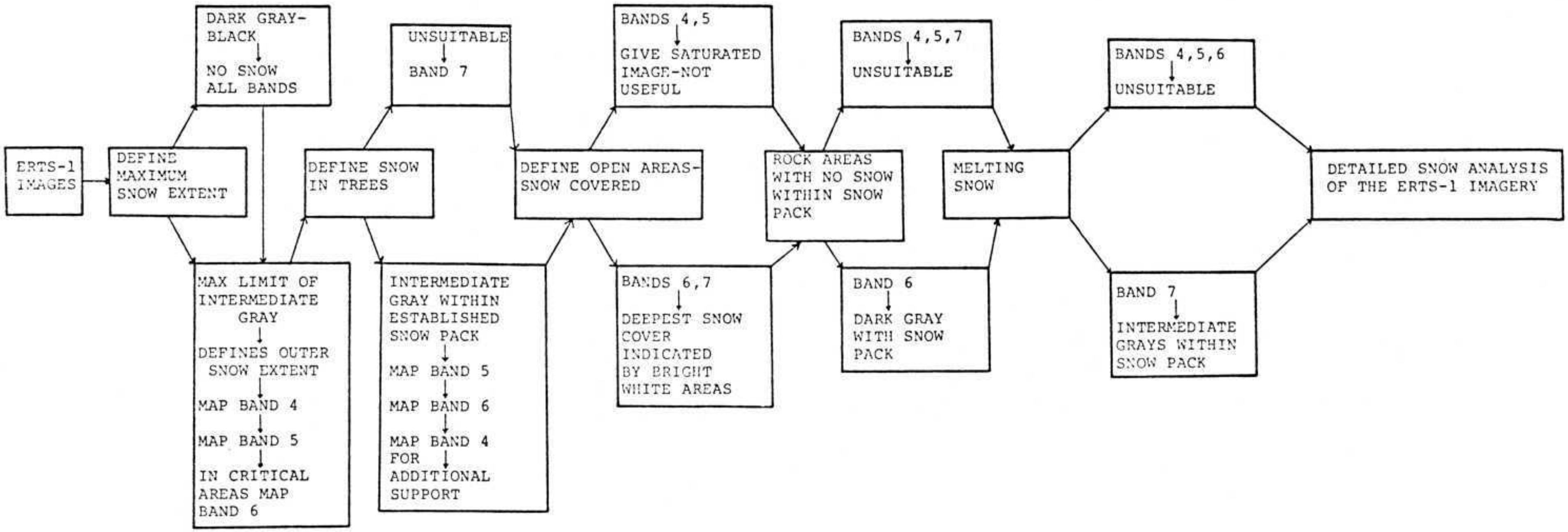


Figure 16: Flow Chart for Snow Pack Evaluation Utilizing ERTS-1 Imagery.

The two primary bands for defining the maximum snow extent are the MSS-4 and 5 images. The researcher should begin mapping the boundary of the gray scale changes in the outer periphery of the snow cover on band 4. After this procedure has been accomplished, band 5 should be mapped in a similar fashion. This provides additional detail of the snow margin which was not apparent on band 4. In questionable areas where the two bands are not in close harmony, band 6 could be used for finalizing the definite snow line. Through the use of these three bands in this initial procedure, the maximum snow extent can be accurately delineated. After the maximum limits of the snow cover have been established all additional snow pack determinations can be made for gray scale changes within that perimeter.

The second step for a complete evaluation entails delineating areas within the snowfield as defined by bands 4 and 5 that are snow covered under coniferous forests. This can be accomplished by using bands 5 and 6. The intermediate gray scale changes should first be analyzed on band 5, followed by evaluations of band 6. This would allow dependable mapping of trees in snow to be accomplished. If additional data is needed regarding snow in trees then band 4 should be consulted.

Snow covered open areas can best be determined using bands 6 and 7. These two bands enable the greatest and deepest snow extent to be accurately delineated.

The only suitable band for evaluating melting snow within the snowfield area as defined on bands 4 and 5 is the MSS-7 image. Band 7 allows both large patches of melting snow and marginal snow pack melting to be determined using the intermediate gray scale tone on this image.

Finally, barren rock outcroppings can be analyzed and mapped through the use of band 6. Delineation of snow free rock outcroppings can be accomplished by delimiting areas of darker gray density changes on band 6. For additional support the MSS-5 image could be used for this purpose as well. However, it would be best to rely only on band 6 for an analysis of rock outcroppings devoid of snow.

Figure 17: High Flight Aerial Black and White Infrared Photograph (1:130,000) of Crater Lake National Park, Oregon (July 3, 1974)

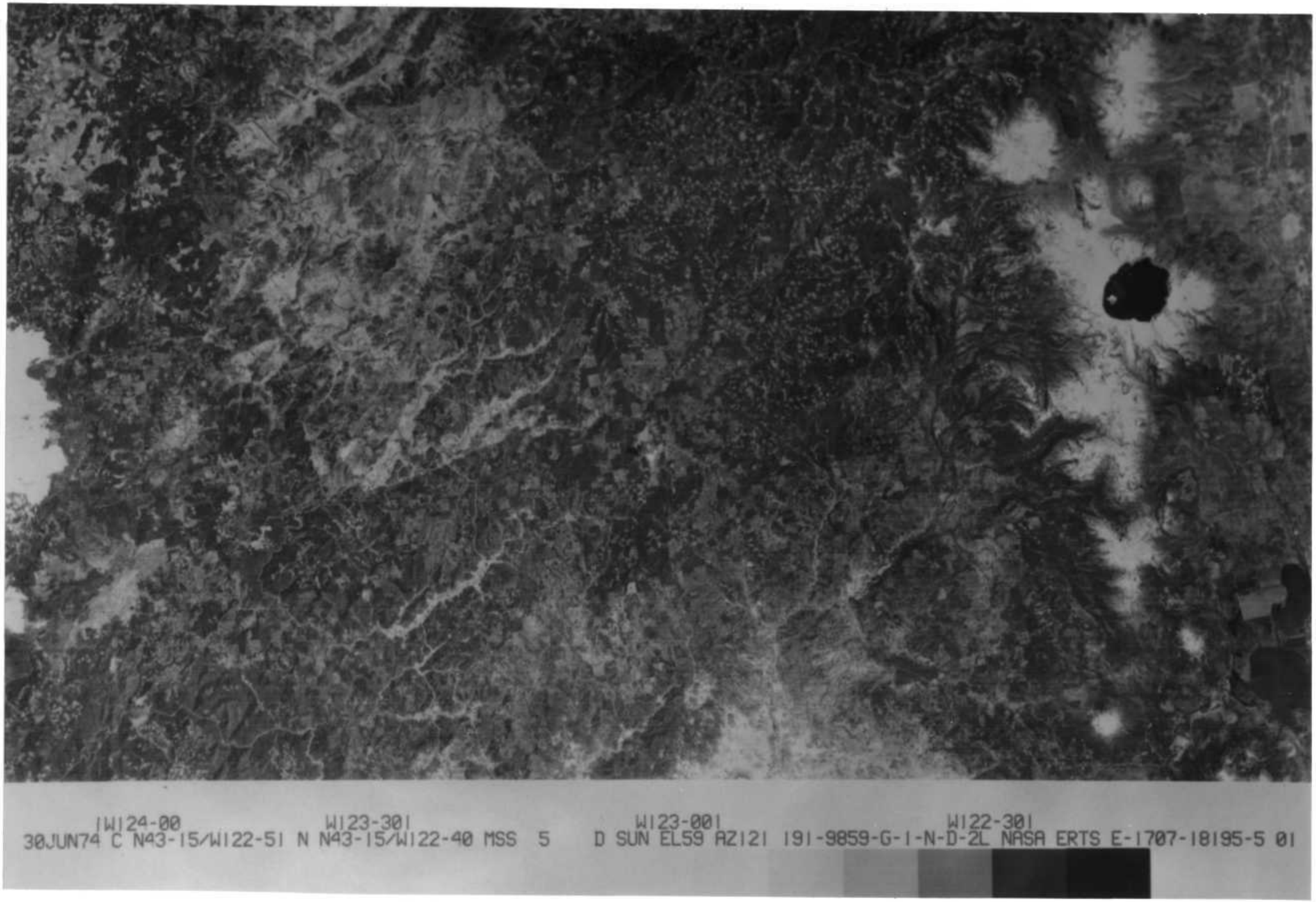


Figure 18: ERTS-1 Image (MSS-5, Scale 1:1,000,000) of Crater Lake National Park and Vicinity, Oregon, June 30, 1974 (Note: This is an example photograph intended to acquaint the reader with the original scale ERTS-1 imagery.)

TABLE 3--Definitions of Codes Used to Cite Critical Areas on the ERTS-1 Images

Symbol	Definitions
A	Break between gray scale density delineating the maximum extent of snow.
A_1	Area of parallax problems causing difficulty in delineating areas of maximum snow extent.
A_2	Gray scale change indicating the presence of snow in areas where snow does not exist.
A_3	Close agreement with the actual snow boundary and changes in the gray scale density using band 6.
B	Snow cover in areas of coniferous forests.
C	Open snow covered areas.
D	Rock outcropping devoid of snow.
E	Area of melting snow.

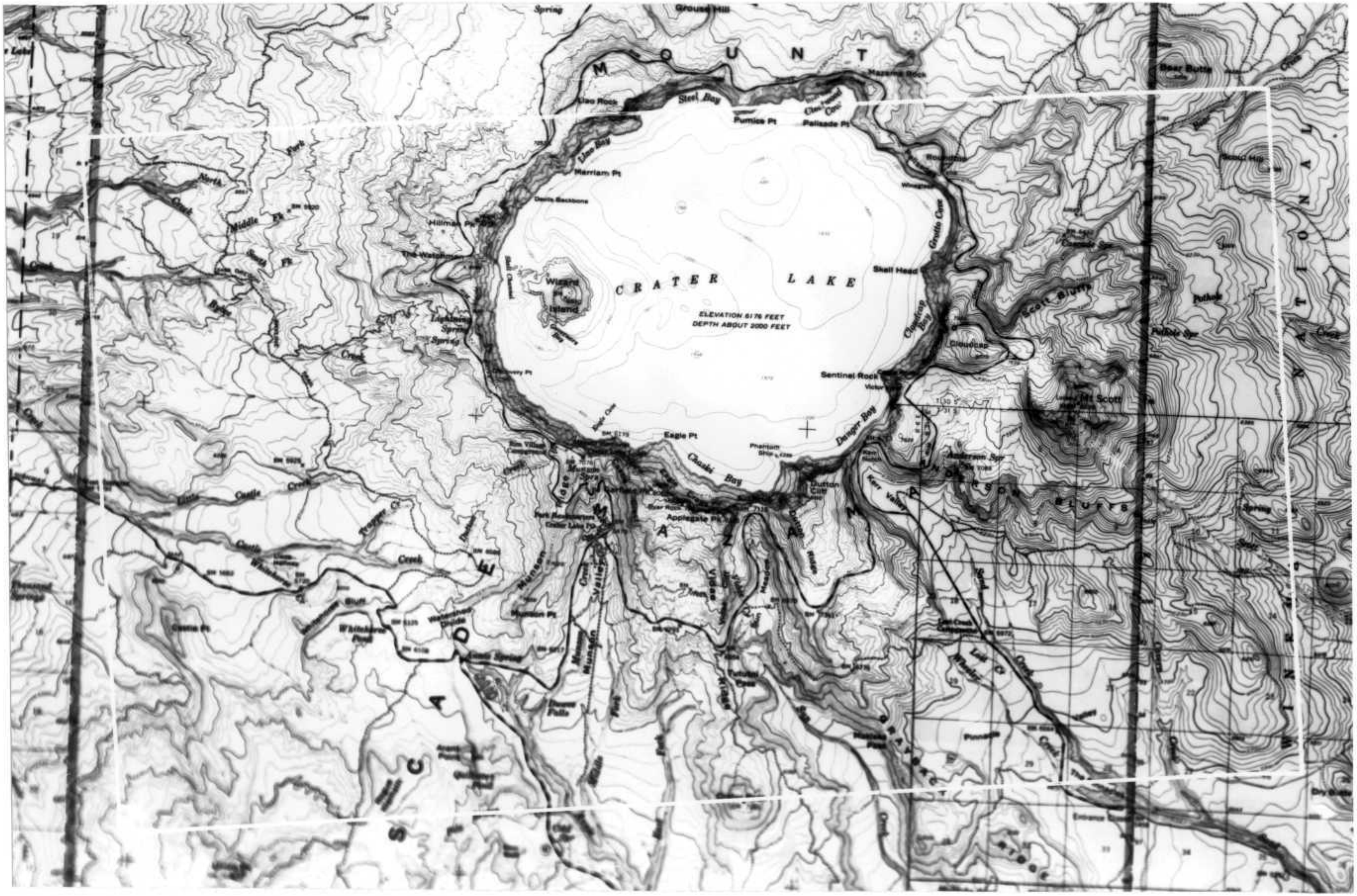


Figure 19: U.S. Geological Survey Topograhical Map of the Study Area, Crater Lake National Park, Oregon.

SCALE 1:62500

CONTOUR INTERVAL 50 FEET
DATUM IS MEAN SEA LEVEL
DEPTH CURVES AND SOUNDINGS IN FEET—DATUM IS LAKE ELEVATION 6176 FEET

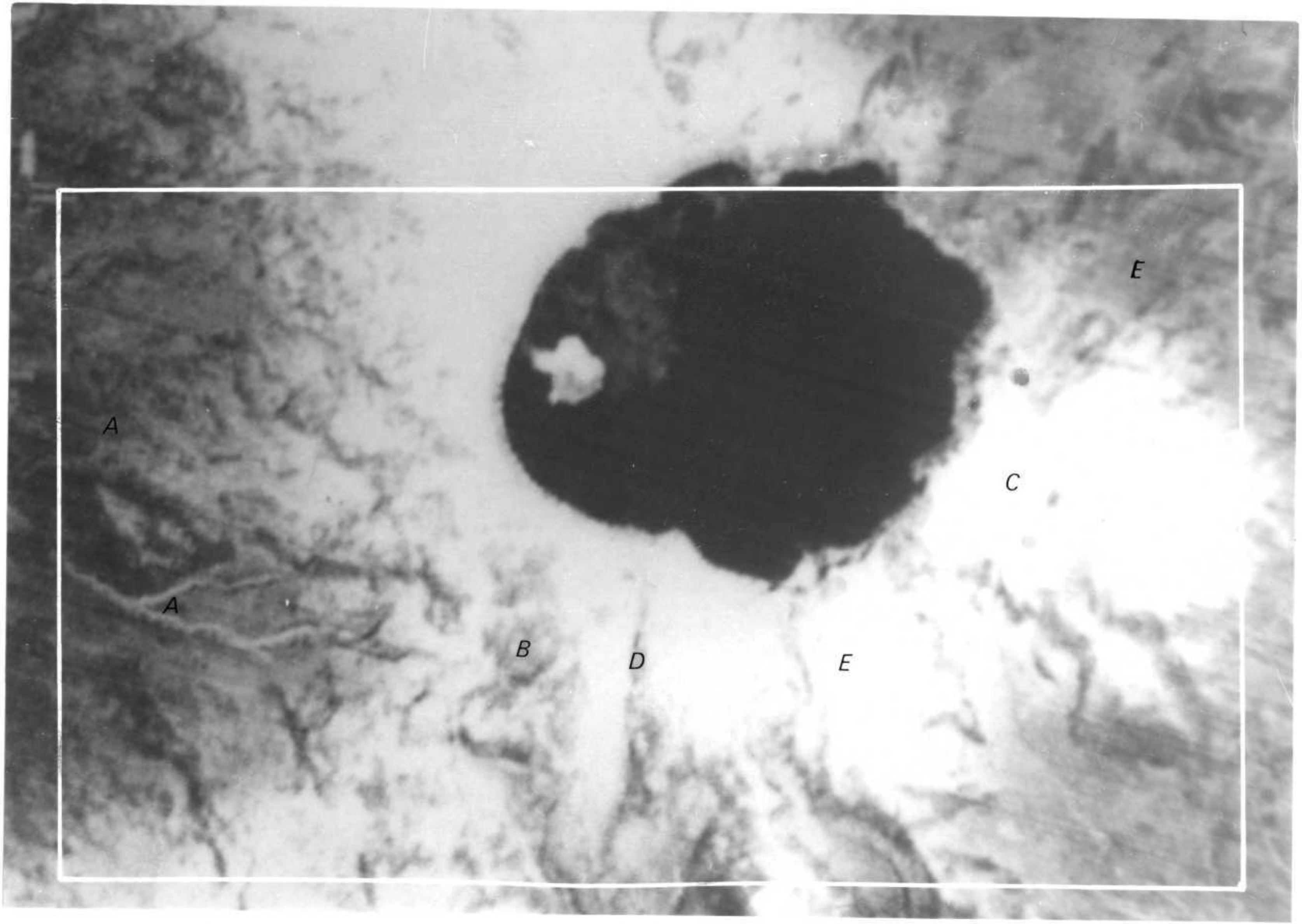


Figure 21: MSS-5 ERTS-1 Image (scale 1:130,000), Crater Lake National Park, Oregon, June 30, 1974. (Note: Definitions of designated letters on the photograph can be found in table 3; boarder indicates study area. The image quality is due to decreased resolution encountered with the enlarged scale and the fact that the photograph is a fourth generation reproduction.)

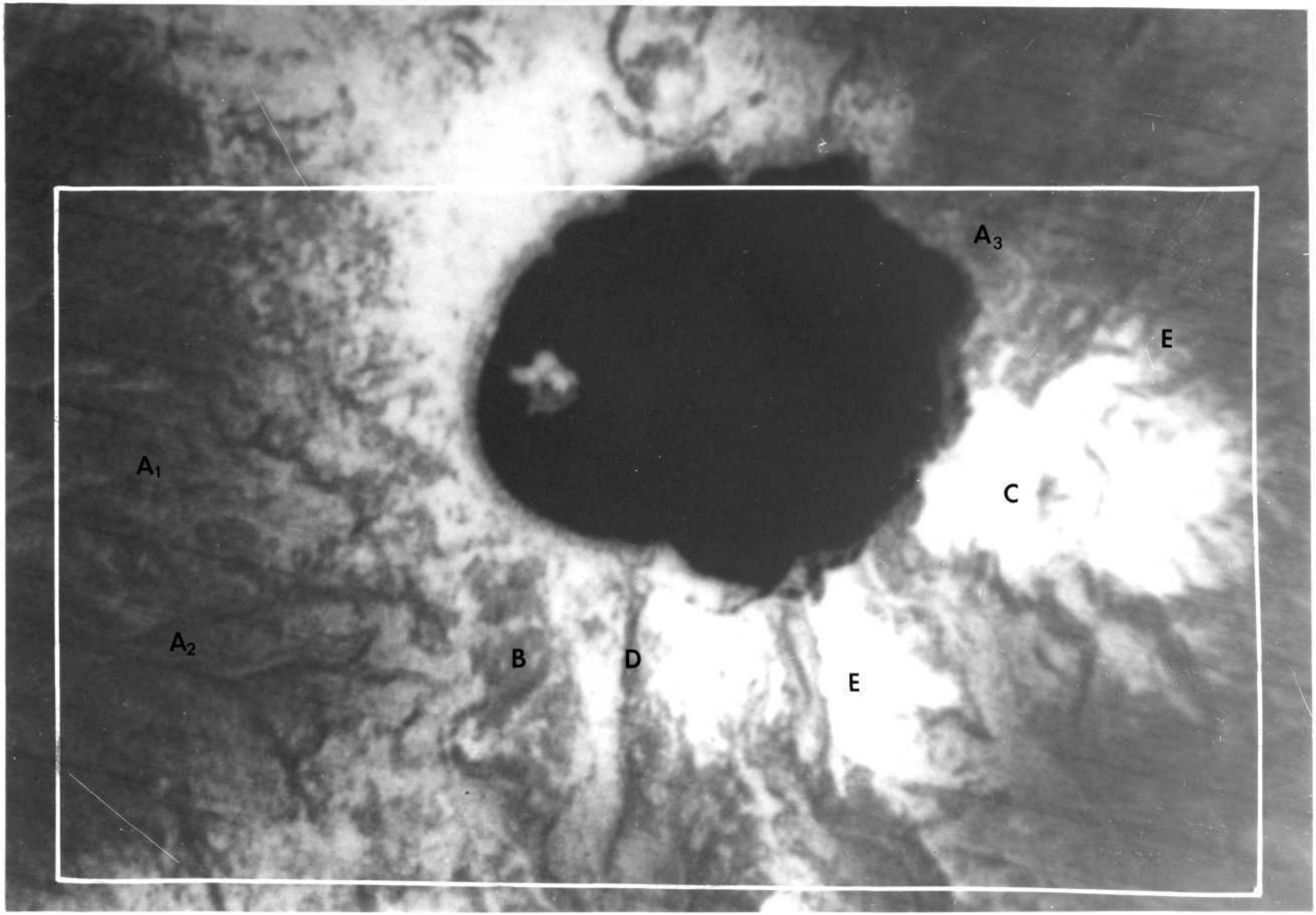


Figure 22: MSS-6 ERTS-1 Image (scale 1:130,000), Crater Lake National Park, Oregon, June 30, 1974. (Note: Definitions of designated letters on the photograph can be found in table 3; boarder indicates study area. The image quality is due to decreased resolution encountered with the enlarged scale and the fact that the photograph is a fourth generation reproduction.)

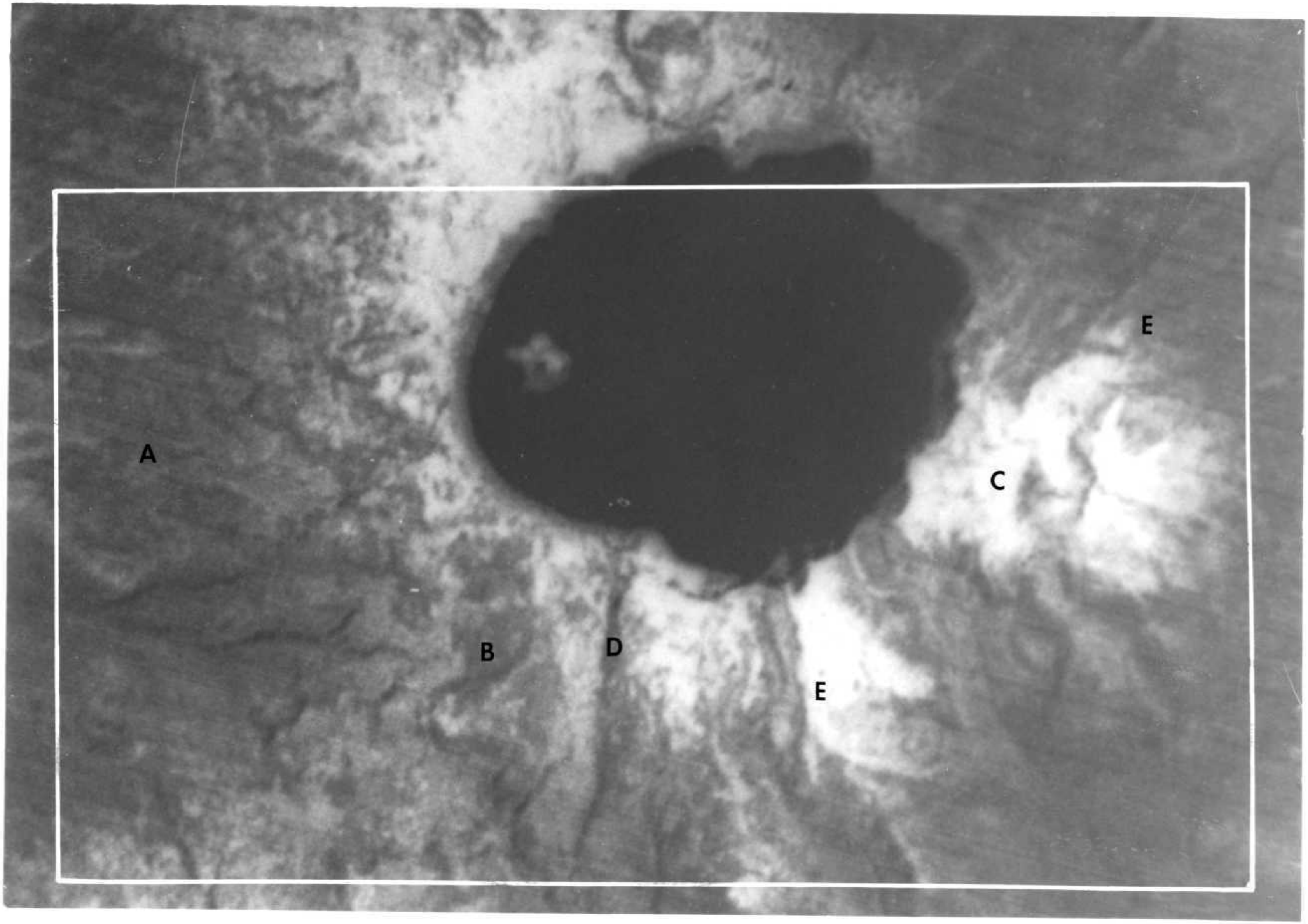


Figure 23: MSS-7 ERTS-1 Image (Scale 1:130,000), Crater Lake National Park, Oregon, June 30, 1974. (Note: Definitions of designated letters on the photograph can be found in table 3; boarder indicates study area. The image quality is due to decreased resolution encountered with the enlarged scale and the fact that the photograph is a fourth generation reproduction.)

VI. POTENTIAL APPLICATION OF ERTS-1 IMAGERY TO SNOW HYDROLOGY

Mountain snowpacks supply most of the water utilized in the western United States. The snowmelt runoff has a direct impact upon the economy of this region which uses the water for irrigation, industrial production, power generation, public consumption and recreation. Adverse effects, such as flooding, can result from too much runoff.

Despite the economic implications of this hydrologic resource, present methods of snow monitoring often cannot provide desired data for remote areas of the earth. Remote sensing using ERTS-1 imagery presently allows the snow hydrologists to observe all areas of snow cover. Sophisticated procedures permit snow to be treated as a variable or parameter while empirical correlations can be made between snow cover and runoff.

Snow Line Mapping

The cartographic application of ERTS-1 imagery has a definite potential in regard to snow line delineation. Studies conducted by James C. Barnes (1973-74), Mark F. Meier (1973-74) and other researchers indicate the validity and the extent to which snow lines can be derived from satellite imagery.

ERTS-1 imagery has been correlated with high flight aerial photographs and snow surveys (aerial and ground-based) to determine the accuracy of snow cover measurement using satellite photography. James C. Barnes (1973) applied ERTS-1 imagery to primary geographic areas in the United States (southern Sierra Nevada, California). Each of these areas are of prime hydrologic significance. The snow line was mapped on the satellite photographs at the edge of the brighter tone without regard to changes in light reflectance within the overall snow pack. These changes in tone were due primarily to the forest effects in the study areas. Barnes (1973) concluded that there was no significant difference between snow detection utilizing ERTS-1 imagery and aerial survey snow charts (figure 24). For each case tested, the percentage of the basin that was snow covered was greater in the satellite photographs as compared to the aerial survey (table 4). Hence, the equivalent snow line (ESA) determined from the ERTS-1 imagery is lower in elevation than the snow line mapped from the aerial survey charts. Thus, it appeared that a greater amount of detail could be mapped from the satellite photographs than that mapped by the aerial observer (based on comparative snow extent).

Significant results have also been obtained by other researchers regarding the application of ERTS-1 imagery to snow line delineation. Donald Baker (1973) verified the accuracy of snow line mapping using satellite photographs for the Great Plains and relatively unforested areas in the midwest. Others who have made significant contributions and reaffirmed the validity of ERTS-1 imagery in snow line

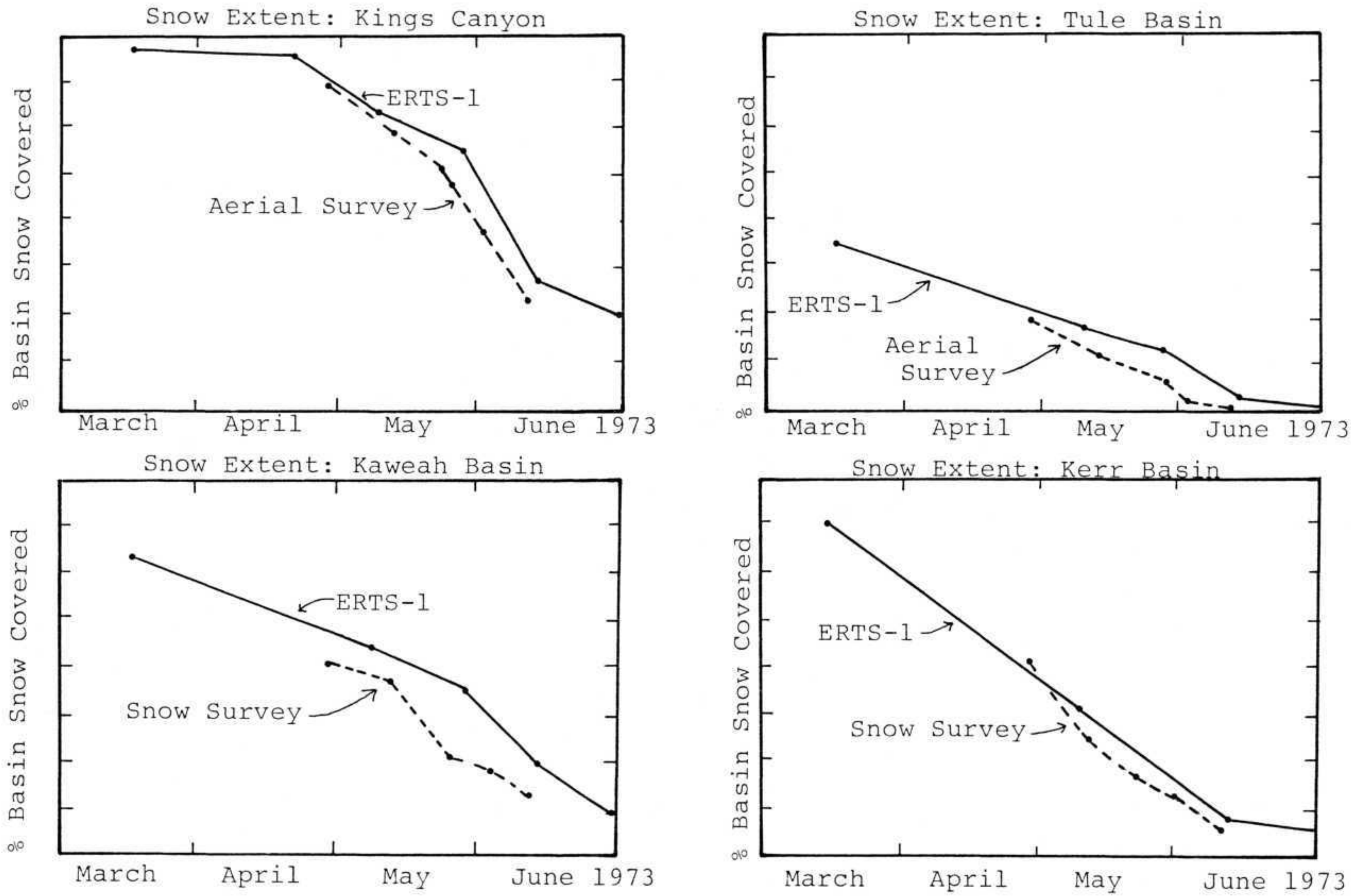


Figure 24: Snow extent in Southern Sierra Nevada mapped from Aerial Snow Survey charts. Values are in percentage of basin snow covered; dates of observation are indicated (Source: James C. Barnes, et.al., Reference #3, p. 990, 1973).

	ERTS			AERIAL SURVEY			DIFFERENCE	
RIVER BASIN	DATE 1973	%**	ESA*	DATE 1973	%**	ESA*	AERIAL %	ERTS ESA
KINGS	20 Apr	75	5700	27 Apr	69	6500	6	800
	8 May	64	7000	11 May	59	7500	5	500
	26 May	56	7800	22 May	52	8100	4	300
	$\bar{x}$						5.0	533
TULE	8 May	16	6400	11 May	11	7000	5	600
	26 May	13	6600	22 May	7	7400	6	800
	$\bar{x}$						5.5	700

Table 4: Comparison between ERTS Data and Aerial Survey Snow Charts for River Basins of Southern Sierra Nevada.

(Source: James C. Barnes, Microfische E73-10833, p. 9, 1973)

ESA*: Equivalent snow line altitude (in feet)

%**: Percent of basin snow-covered

delineation include D.R. Wiesnet and D.F. McGinnis, Jr. (1973) and Harold Haefner (1973).

Snow Pack

The ability to monitor the snow pack in a watershed has significant hydrologic implications. Leaf (1969) determined that a functional characteristic exists between snow extent during the melt season and accumulated runoff. He concluded that the magnitude of seasonal snowfall peaks and the approximate timing of snow melt can be determined from snow cover depletion relationships.

Satellites have been useful in the past for monitoring the snow pack in watersheds. Snow surveys have been aided by more recent, high resolution imagery from the ERTS-1 satellite. ERTS-1 imagery has been successful in quantifying information about the water content and the wetness of the snow pack in basins and watersheds. The seasonal and daily average of the basinwide snowmelt has also been monitored by ERTS-1 photography.

The image on the ERTS-1 photograph allows accurate identification of the drainage basin and terrain pattern. Because of the clarity of these features the snow can be accurately located and measured. The ERTS-1 image is of some limited value since very little data can be obtained on snow depth. However, snow volumes determined by photogrammetry can be multiplied by the average density of the snow to estimate the amount of water contained in the snow pack.

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Runoff from Snow Melt

Experiments from ERTS-1 imagery indicate that satellite monitoring of mountain snow cover (aerial extent) can be feasible and provide important data to the snow hydrologist. During the spring and summer months, accurate data are necessary to predict stream flow into hydroelectric, flood control or irrigation reservoirs.

V.V. Salomonson (1973) used satellite photographs (Numbus 3 and 4) to plot the relationship between mean monthly discharge of the Indus River and snow cover observed in the space photographs (figure 25). There is good agreement between the monthly mean discharge and the observed snow cover during the period of major snow melt (April to late July). Similar results can be expected from the application of ERTS-1 images to other watersheds.

Studies conducted by Mark F. Meier (1973) indicate the potential application of ERTS-1 images in regard to forecasting runoff volumes from the snow pack. Using satellite images and high altitude aircraft photographs, maps of the snow extent were prepared for the Thunder Creek drainage basin (272 km^2) near Newhalem, Washington. Computations were then made to determine snow melt runoff and loss of snow mass. These calculations were based on the hydrologic balance procedure developed for the analysis of International Hydrologic Decade Glacier Basins (Meier, Thangborn, Mayo and Post, 1971; Tanborn, 1968). These data were then used

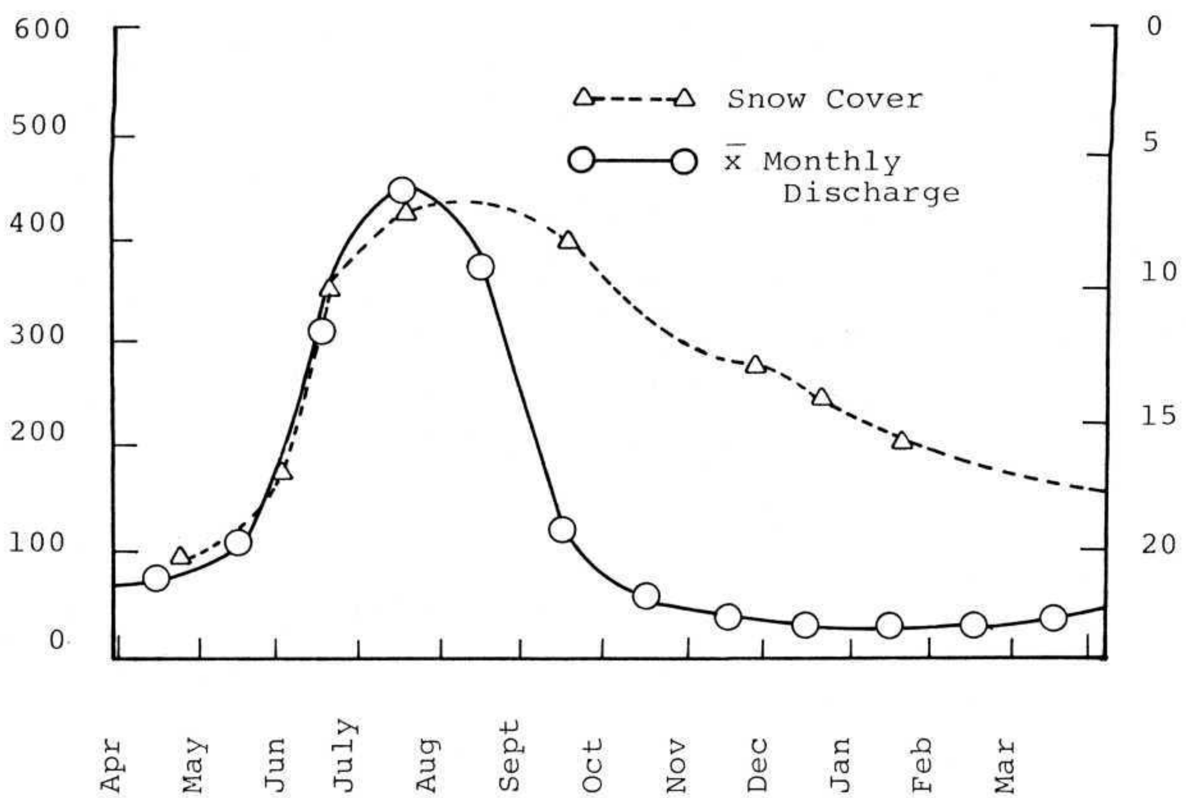

Figure 25: A plot showing the relationship between the percent snow cover over the Indus River watershed and the mean monthly discharge in the Indus River near Attock in West Pakistan. The snow cover area was obtained from the observations of the Minbus 3 and 4 Image Dissector Camera System (Source: V.V. Salomonson, Reference #21, p. 445, 1973).

with the ERTS-1 images and U-2 photographs to calculate the rate of snow melt (in mm of water equivalance = W.E.). The calculated rates were then compared to the actual snow melt rate recorded at a gaging station 15 km south of Thunder Creek (figure 26).

Other important hydrologic quantities can also be determined through the use of ERTS-1 imagery (e.g., snow melt rates). Snow melt rate is very difficult to determine at frequent time intervals (i.e., daily or weekly) without appropriate equipment and at single points. Matter of fact, the determination of snow melt rate over an extensive area is essentially impossible to measure with existing techniques. However, by using ERTS-1 imagery combined with real-time hydrologic data, calculations can be made to determine these results. In midsummer, 1972, the snow pack in Thunder Creek changed its area at a rate of 1.6 percent per day. If one assumes a four percent standard error in each area measured, then calculations should be based on periods as short as from three to five days. [5]

Thus, as these studies indicate, ERTS-1 imagery can provide a method of frequent, routine and confident measurement of snow cover extent. Reservoir inflow forecasts can then be made on a basis of plotting snow cover versus subsequent runoff volume. Since snow depletion rates are highly correlated with seasonal runoff volumes and this runoff is usually uniform throughout the years, ERTS-1

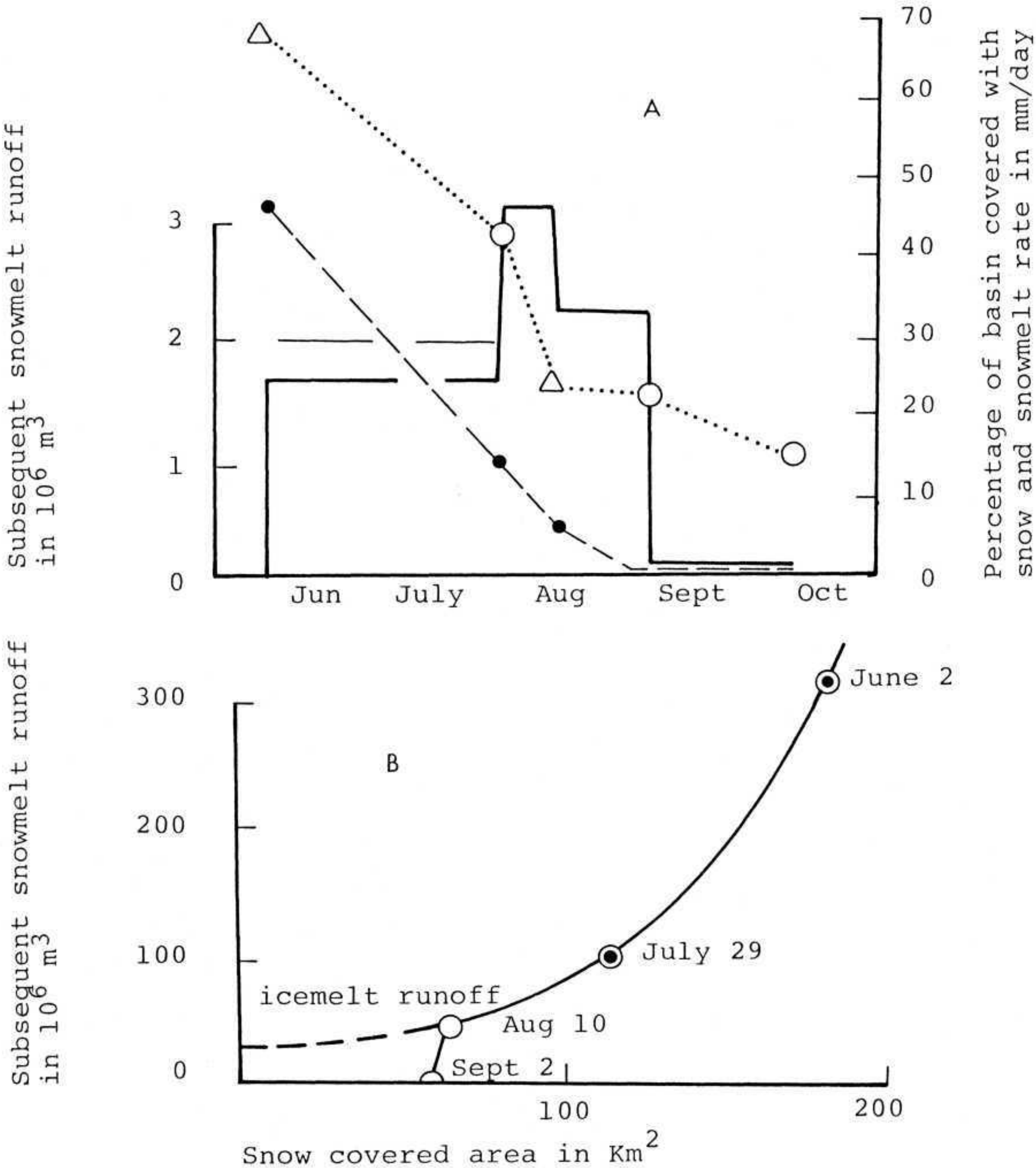

Figure 26(A): Snow-covered area (dotted line) subsequent snowmelt runoff volume (dashed line) and rate of snowmelt (heavy line) in the Thunder Creek Drainage basin; thin line is average observed snowmelt rate. Triangles are data from 19.8 km altitude aerial photographs; circles are data from ERTS-1. (B): Subsequent snowmelt runoff as a function of snow-covered area, Thunder Creek drainage basin. (Source: Mark F. Meier, Reference #4, p. 866, 1973).

images can be used to develop graphs as mentioned above. Hence, fast measurement of the snow extent can be immediately converted to snow pack, storage and stream flow forecasts. The application of this information would allow more precise regulation of reservoirs, less water wasted, the sale of additional firm power and less impacts from excessively high or low stream flows.

Remote sensing using ERTS-1 images can also be applied to hydrologic studies regarding "the source area concept." This concept assumes "that surface and subsurface runoff is geographically concentrated at hydrologically active portions of a basin."[6] Two processes (interception of precipitation and subsurface flow by the stream channel) produce storm runoff. ERTS-1 images have been used by Ishaq and Huff (1973) to identify these factors in a watershed. Using color infrared film they were able to develop a more accurate runoff generation model and apply their findings to the areas of water quality, stream classification, rural drainage, erosion and soil conservation.

Problems and Limitations

Even though the ERTS-1 imagery has a definite potential application to snow hydrology it also has some limitations. The following points indicate the nature of the problems that the snow hydrologist encounters in the utilization of ERTS images.

1. Clouds: are of comparable brightness to snow and sometimes obscure terrestrial features.
2. Vegetation: influences tones of gray and the location of the snow line in satellite photographs.
3. Slopes and Terrain: influences the variations in brightness of snow and other features.

The first problem, clouds, appears not to be a serious deterrant to the use of ERTS-1 data for snow hydrologic application. Even though both snow and clouds have similar reflectance, snow can be differentiated by its sharper than typical boundary. Also, snowfields have a more uniform reflectance than clouds. However, photographs that have complete cloud cover over the watershed being studied definitely hinder that research.

The effects of vegetation (especially forests) and terrain greatly influence the appearance of snow as seen in ERTS-1 imagery. William C. Draeger and Donald T. Lauer (1974) proposed a fast, simple and effective method which helps the photographic interpreter overcome these problems. Light aircraft photographs (35 mm) were used as a source of "ground truth" and were taken at the same time as the ERTS-1 overflight. The researcher then simultaneously views both summer and winter ERTS-1 color composites of the study area. The summer image provides information on vegetation types and density while the winter photo gives information on snow distribution. By amalgamating the information obtained from both photographs, the researcher can make a more accurate estimate of the snow extent (especially in heavily forested areas). In a test on the Feather River watershed, California, the researcher was able to obtain a 98.4 percent accuracy delineating the snow cover (total training for the researcher was 12 hours).[6]

VII. RECOMMENDED FUTURE STUDIES

Previous research and as well, my own research, clearly indicate the great potential ERTS-1 imagery has to the field of snow hydrology. The necessity for further application of satellite imagery is apparent. With refined and expanded remote sensing interpretation techniques, accurate hydrologic forecasting will evolve. There are three fields of study which need to be pursued in order to facilitate the advancement of ERTS-1 images in the field of snow hydrology. These areas are: 1) spatial examinations, 2) snow pack response to environmental stimulus and 3) application of computer science techniques.

Spatial Examinations

The study area at Crater Lake National Park provided suitable snow pack coverage for this initial study. However, in order to apply the results obtained in the research for hydrologic purposes, larger study areas are required. It would be appropriate to apply the techniques utilized in this research to large drainage basins or entire mountain systems, such as the High Cascades or Wallowa Mountains. An analysis of drainage basins or mountain systems using ERTS-1 images would allow direct forecasting of snowmelt rates, predictions of stream discharge related to snow pack depletion and the development of accurate runoff generation models in these larger study areas.

Snow Pack Response to Environmental Stimulus

Further application of the snow pack response to environmental stimulus is also needed to more accurately decipher information on the ERTS-1 imagery. Spatial snowmelt characteristics are essentially the same each year although the temporal aspect of that melt is dependent on the quantity and quality of the snow. Through a detailed analysis of the observed snowmelt patterns over a number of years the researcher would be able to formulate a general ablation pattern for the snow pack. This pattern could then be directly applied to the ERTS-1 imagery to determine the melt stage of the snow pack. The final interpretation of this data would enable more accurate predictions for the future occurrence, rate and amount of snowmelt in the study area.

Application of Computer Science Techniques

The application of advanced computer science techniques is manditory to establish greater reliability for hydrologic purposes using ERTS-1 imagery. The interjection of computer techniques would allow more accurate data to be obtained while maintaining a standardized approach throughout the research.

Procedures utilized in this research could be employed in future studies. Expansion of future research could determine gray scale densities to establish specific densities of gray in the snow covered area. A densitometer, such as the Welch Densichron could be used to accurately determine these gray scale densities. The Welch Densichron results would serve as a basis of initial evaluation of the snow cover on the ERTS-1 images in all spectral bands. In addition, magnetic tapes for critical snow extent areas could be ordered from the Earth Resource Observation System Program (EROS) Center in Sioux Falls, South Dakota. This data could then be fed into a computer where decodifying of the marginal information would occur. This process would serve to establish the frequency distribution of gray tones throughout the critical area. The data obtained would then be reorganized and given back to the computer. This would permit the data output to come back in the form of computer prints which would delineate the snow extent. Hence, the computer would map the snow cover from the ERTS-1 images in a rapid and accurate fashion.

Computer techniques could also be used to experiment with color ERTS-1 imagery. The researcher could determine which combinations of color photographs could be amalgamated by the computer to enhance the snow pack and its melt characteristics. This process would enable the researcher to eliminate certain terrestrial features, such as the forest cover, which effect the appearance of snow on the ERTS-1 photographs.

VIII. CONCLUSION

Snow is a water resource for which ERTS-1 imagery has great potential in the providing of significant information to the snow hydrologist. The ability of this satellite to provide a means whereby snow pack conditions can be accurately monitored in accessible and inaccessible regions of the world has immense ramifications. The prediction of snowmelt runoff utilizing the ERTS-1 images would have a direct impact upon the economy of a region, especially the Pacific Northwest, which uses this water for irrigation, industrial production, power generation, public consumption and recreation.

Through an analysis of the fluxes of heat energy within a study area, energy budget equations can be formulated and snowmelt summary graphs can be constructed. This would enable more accurate snowmelt rates to be developed. In addition, the snow pack response to environmental conditions could be examined to more accurately decipher information on the ERTS-1 imagery.

The high resolution photography from the ERTS-1 satellite produces an image which provides a great amount of information about the snow extent. This research has evaluated ERTS-1 imagery to determine potential application of these following points:

1. Scale Utilization: accurate and detailed snow extent maps can be prepared from ERTS-1 imagery

using a large scale of 1:130,000

2. MSS-4 Image: provides a good snow cover image, allows excellent delineation of the snow extent and indicates snow in coniferous forests, indicates pumice areas well, but poorly indicates rock outcroppings devoid of snow.
3. MSS-5 Image: combined with band 4, it provides a good basis for delineating snow extent, portrays snow cover in coniferous forests well, does a good job indicating open areas with snow but does not distinguish well between the two, provides only a poor to fair estimate of the rock outcroppings and pumice areas devoid of snow and it does a poor job delineating areas of melting snow.
4. MSS-6 Image: is quite versatile, but is of limited use for delineating the maximum limits of the snow-field, does a very good job indicating snow in trees, allows excellent evaluations for rock outcroppings devoid of snow and does a fair job delineating areas of melting snow.
5. MSS-7 Image: gives the greatest difficulty in detecting general characteristics of maximum snow extent, i.e., it poorly indicates the margins of the snow cover, is unsuitable for detecting snow in coniferous forests, does an excellent job defining open areas with snow, makes rock

using a large scale of 1:130,000

2. MSS-4 Image: provides a good snow cover image, allows excellent delineation of the snow extent and indicates snow in coniferous forests, indicates pumice areas well, but poorly indicates rock outcroppings devoid of snow.
3. MSS-5 Image: combined with band 4, it provides a good basis for delineating snow extent, portrays snow cover in coniferous forests well, does a good job indicating open areas with snow but does not distinguish well between the two, provides only a poor to fair estimate of the rock outcroppings and pumice areas devoid of snow and it does a poor job delineating areas of melting snow.
4. MSS-6 Image: is quite versatile, but is of limited use for delineating the maximum limits of the snowfield, does a very good job indicating snow in trees, allows excellent evaluations for rock outcroppings devoid of snow and does a fair job delineating areas of melting snow.
5. MSS-7 Image: gives the greatest difficulty in detecting general characteristics of maximum snow extent, i.e., it poorly indicates the margins of the snow cover, is unsuitable for detecting snow in coniferous forests, does an excellent job defining open areas with snow, makes rock

outcroppings devoid of snow nearly impossible to discern and is good in its ability to detect melting snow.

6. <u>Multispectral Snow Mapping Procedures</u>: should begin by defining the maximum limit of snow and delineating it using band 4 following by band 5 (in questionable critical areas band 6 should be consulted). Next, within the previously defined snow area, snow in coniferous forests should be determined using bands 5 and 6, further information can be determined from band 4. Following this second step bands 7 and 6 should be utilized to map open areas which are snow covered. Analysis of barren rock outcroppings can be accomplished through the use of band 6. Finally, band 7 should be used to evaluate melting snow.

This research clearly indicates that the ERTS system is definitely viable as a tool in the field of snow hydrology. The ERTS system can furnish information to permit automated extraction of information and the generation of a usuable product for the snow hydrologist. The hydrologist can then apply these data to more accurately monitor and predict the economic and social impact of snow.

APPENDIX

This following passage is quoted from:

EARTH RESOURCES TECHNOLOGY SATELLITE INFORMATION

[Modified from National Aeronautics and Space Administration, "Earth Resources Technology Satellite Educational Package"]

I. What ERTS is and what it does...

ERTS (Earth Resources Technology Satellite) is a butterfly shaped observatory (fig. 1) flying in a 570 mile (920km) circular orbit which is nearly polar. From this vantage point its imaging systems provide useful information concerning agriculture and forest resources, mineral and land resources, water resources, marine resources, land use and environmental quality, and ecology.

ERTS circles the Earth every 103 minutes or 14 times per day (fig. 2). The pass is from north to south at an angle of 80° retrograde to the equator. Each pass covers a region 115 miles (185km) wide, however, there is some overlap between the preceding and succeeding passes. After 18 days or about 252 passes the satellite returns to the same position. In other words ERTS covers the entire globe every 18 days.

The sun-synchronous nearly polar orbit was specifically selected for the sun angle. On each north to south pass the satellite crosses the equator at 9:42 a.m. local time.

The Return Beam Vidicon (RBV) cameras consist of three cameras each viewing the same 115 by 115 mile (185 by 185km) area. The three RBV cameras view the same area in three different spectral bands, the blue-green (475 to 575nm), the red (580-680nm) and the near infrared (690 to 830nm). These cameras do not contain film but rather their images are stored on photosensitive surfaces within each vidicon camera which in turn is scanned by an internal electron beam to produce a video picture. This process requires 11 seconds to read out and transmit all three pictures. The RBV cameras will repeat the cycle each 25 seconds producing overlapping pictures of the ground scene below with 10 percent overlap. The RBV camera lenses have a diagonal field of view angle of 15.9°.

The Multispectral Scanner Subsystem (MSS) covers the same area as the RBV system in four wavelength bands, the green (500 to 600nm), red (600 to 700nm), the near infrared in two bands (700 to 800nm and 800 to 1100nm). This scanner returns a strip image in these four bands.

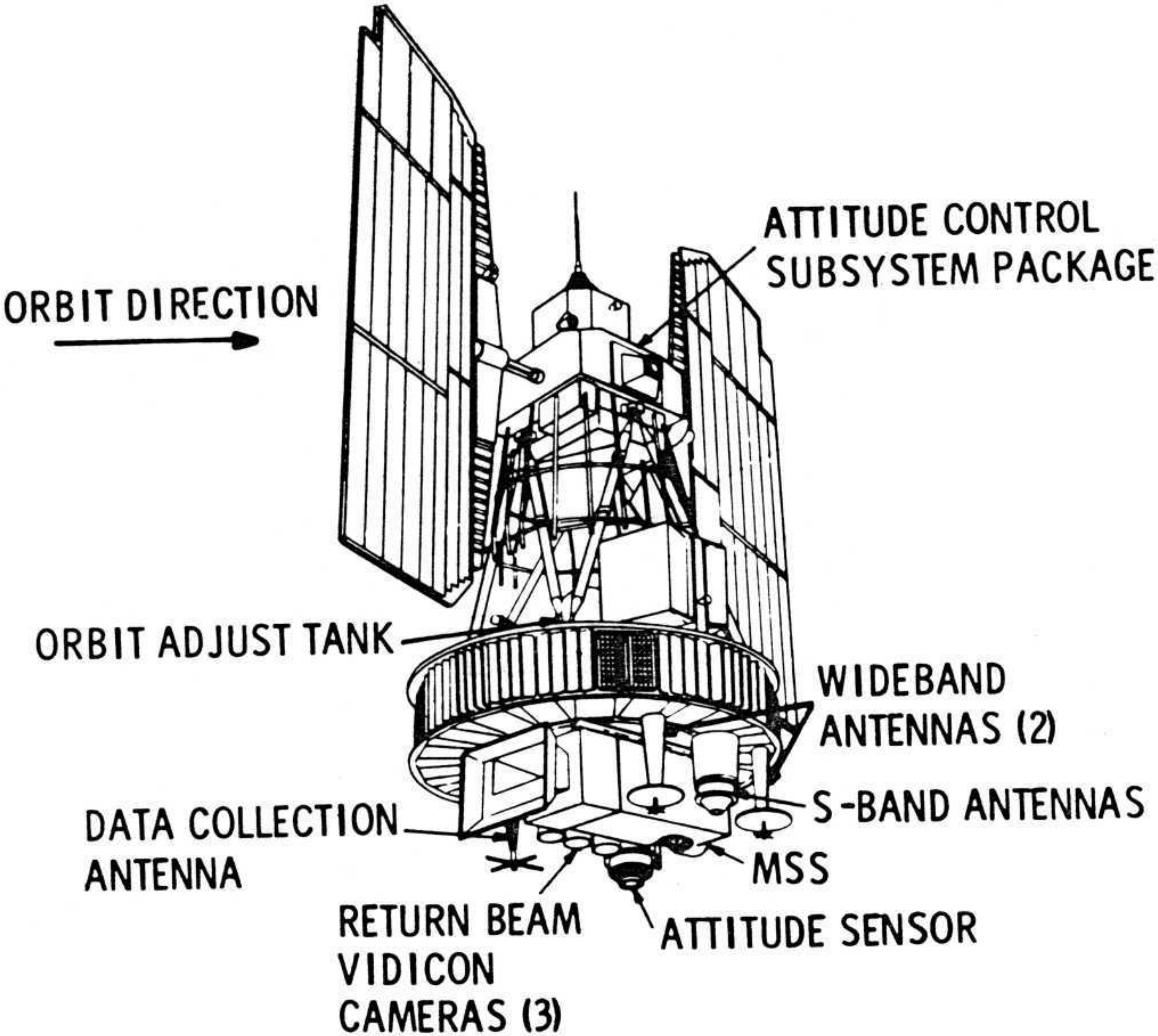

FIGURE 1. - ERTS OBSERVATORY CONFIGURATION

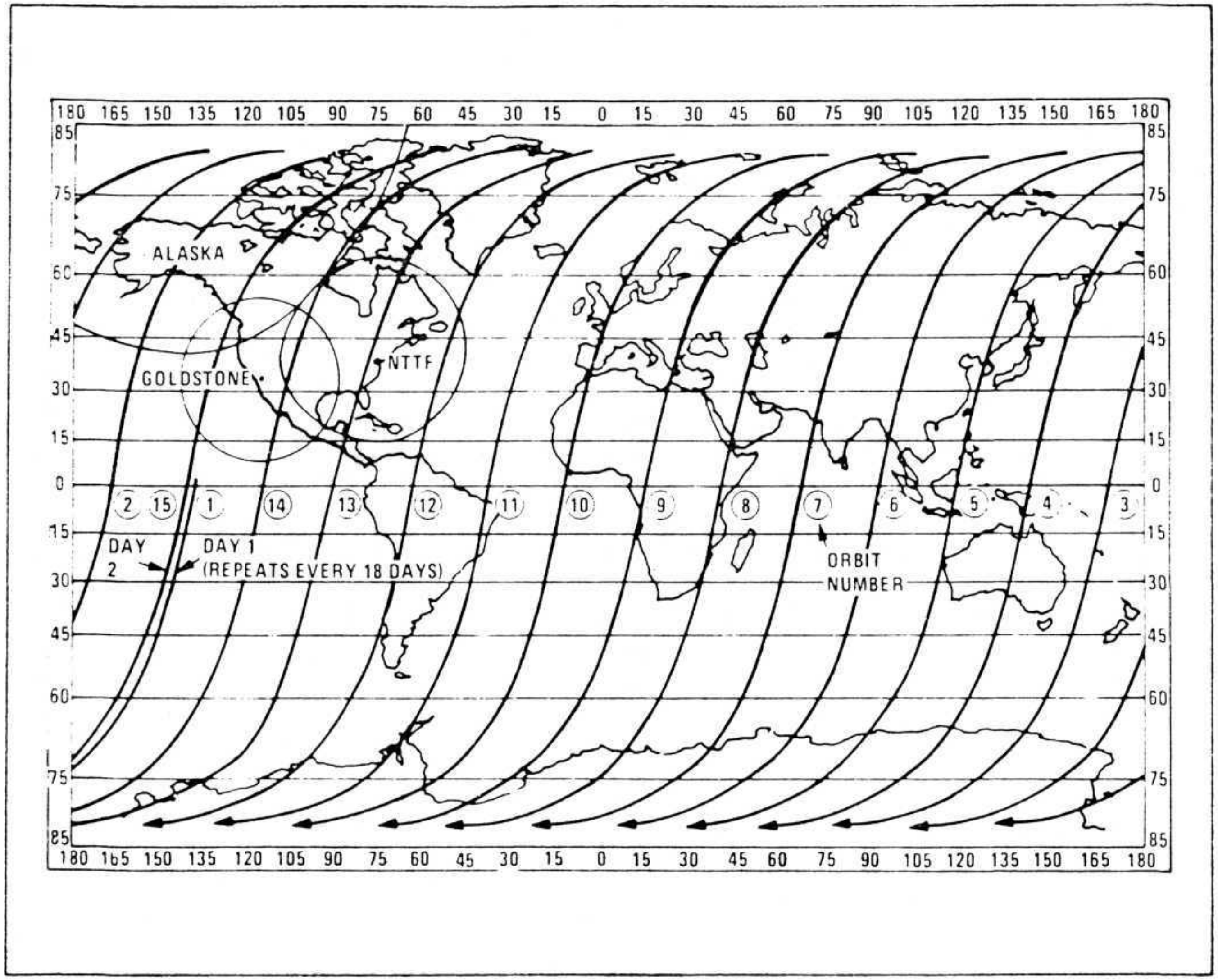

FIGURE 2. - ERTS ORBITS

The Data Collection System (DCS) collects information from some 150 remote, unattended instrumented ground platforms and relays it to NASA ground stations for delivery to the user.

Two Wide Band Video Tape Recorders are used to record image data from those areas outside the range of U.S. ground stations for later playback.

II. Remote sensing and the type of imagery obtainable from ERTS

Remote sensing is simply measuring or observing something from a distance. A camera is a remote sensor in that it records the shape and color of an object by its reflected light without touching the object.

Remote sensing is one of the most rapidly advancing technologies. Unlike many technological advances, it does not pollute and it has been used in a variety of ways by industry to perform what is called "non-destructive testing." In fact, remote sensing may be used to preserve the quality of the environment by providing means of monitoring the Earth, by detecting pollution, and by providing information for the better utilization of our natural resources.

Human beings collect information through their five senses; however, there is much information which they cannot detect. Most of the radiation which is reflected or emanated from the Earth cannot be detected by the human eye. Infrared light lies just beyond our vision, and healthy green vegetation is brighter in the infrared than in the green that our eyes detect.

Electromagnetic energy may be expressed by either the frequency, wavelength, or wave-number. Different scientific disciplines prefer particular units. For example, the red light of excited hydrogen (called the H-alpha line) may be expressed as 6563Å, 656.3nm, 0.6563μm, micrometers or microns, 4.568×10^{14} Hz (or cps), or 15,236.9K (Kaysers or cm^{-1}).

In biology and chemistry the nanometer (10^{-9}m) is now the most frequently employed unit, although the micrometer (μm, 10^{-12}m) is commonly used in remote sensing.

The wavelengths of the electromagnetic spectrum commonly used in remote sensing range from about 100nm (x rays), 100nm to 400nm (ultraviolet), 400nm to 700nm (visible), 700nm to about 3000nm (infrared and beyond which lie the the microwaves, radar and radio.

Objects having different physical and chemical properties tend to radiate different amounts of energy in the form of different wavelengths of electromagnetic energy.

No single instrument can measure this entire spectrum. It is therefore necessary to use several devices.

The multispectral scanner and return beam vidicon cameras on ERTS I take pictures in desired wavelength bands. Green band 500 to 600nm. This band appears green to the naked eye. Water is quite transparent in this band which tends to enhance features contained within water such as sediment. Light scattering in the atmosphere makes "seeing" in this band difficult at times. Red band (600 to 700nm). This band appears red to the eye. Unlike the green band, the red easily penetrates the atmosphere. This is good for land use mapping where regional population patterns need to be observed against the vegetation patterns. The red band shows good contrast between natural surface cover such as vegetation which absorbs most of this energy against man-made structures which strongly reflect this energy. Many man-made structures appear very bright against dark appearance of vegetation. Bare soil is often highly reflective in this band, so that deserts are best seen in this band. Infrared band (700 to 1100nm). This is invisible to the human eye. Water appears black in the infrared because water almost totally absorbs the radiant energy in these wavelengths. A significant characteristic about the infrared bands is that vegetation appears bright and water appears dark. As a comparison, vegetation is as bright in the infrared as snow is in the visible region.

The average green leaf reflects about 20 percent of green light and absorbs the other 80 percent. It absorbs approximately 95 percent of red light due to absorption by chlorophyll and is frequently called the chlorophyll absorption band. It *reflects approximately 80 percent of infrared light and transmits* the other 20 percent. The brightness of vegetation depends upon several things. First, the type of vegetation, i.e., big leaves will be brighter than small ones. Hardwood trees (deciduous) show up brighter than pine (evergreen). Because of leaf thickness, tobacco shows up brighter than wheat. Second, in the infrared, crop brightness depends upon plant health. Healthy crops, in the infrared will be much brighter than diseased vegetation.

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III. How ERTS imagery may be obtained

ERTS imagery may be obtained at cost from several sources: EROS (Earth Resources Observation Systems), NOAA (National Oceanographic and Atmospheric Administration), and Dept. of Agriculture.

The RBV images cover 115 by 115 statute miles (185 by 185km) and are 7.3 inch square (18.5cm^2) images on standard 9-1/2 inch (24cm) paper. The image scale is 1:1,000,000.

The MSS consists of successive scan lines cross-track and is put into a frame format which matches the RBV by the NASA Data Processing Facility (NDPF).

The annotations list the sensor, time of exposure, orbit number, sub-satellite point, picture center location, sun azimuth, and elevation angles, spacecraft heading, spacecraft attitude, and ground receiving site identification.

The spectral band identifiers in the annotation block are arranged so they show through without obscuring each other when a color composite is made. Therefore the spectral bands used to make each color composite can be readily identified.

The Department of the Interior's Earth Resources Observation Systems (EROS) Data Center is located at 10th and Dakota Avenue, Sioux Falls, South Dakota 57198.

The EROS Data Center staff will assist the user in locating imagery to suit individual needs. They respond to inquires by telephone, letter, and personal visits.

The computerized imagery storage and retrieval system is based upon a geographical system, including the standard grid, supplemented by such information as date and scale. The staff will convert inquiries into searches of the computer based system. They will also assist in ordering reproductions. Visitors to the Center may consult the browse files to evaluate the frames of a particular interest before placing a purchase order.

The user may ask for pictures which include a particular map grid coordinate and indicate that only those available frames with less than a given amount of cloud cover are acceptable. In some cases clouds are an important phase of the study, whereas in others they may obliterate the desired ground features. One may also specify the desired bands (green, red, infrared, etc.), a color composite or a black and white of the color composite.

BIBLIOGRAPHY

Baker, Donald R., "The Remote Sensing of Snow Fields from Earth Satellites," NASA Symposium on Significant Results Obtained from the Earth Resources Technology Satellite - 1, (USGPO, Vol.1, Sec.B, 1973), pp. 1213-1224.

Barnes, James C., "Use of ERTS Data for Mapping Snow Cover in the Western United States," (NASA-CR-133338; Microfische E73-10833, 1973).

Barnes, James C. and Clinton J. Bowley, "Mapping Snow Extent in the Salt Verde Watershed and the Southern Sierra Nevada Using ERTS Imagery," NASA Symposium on Significant Results Obtained from the Earth Resources Technology Satellite - 1, (USGPO, Vol.1, Sec.B., 1973), pp. 977-993.

Burgy, Robert H. and V.R. Algazi, An Assessment of Remote Sensing Applications in Hydrologic Engineering Snow Cover Monitoring (Satellite), (Davis, California: The Hydrologic Engineering Center, Corps of Engineers, U.S. Army, 1972).

Cooper, Charles F., "Snow Cover Measurement," Photogrammetric Engineering, (Vol.31, 1965), pp. 611-619.

[4]Davar, Kersi S., "Peak Flow - Snowmelt Events," in Donald M. Gray (Ed.), Handbook on the Principles of Hydrology, (Secretariat, Canadian National Committee for the International Hydrological Decade, 1970), pp. 9.1-9.22.

[6]Draeger, William C. and Donald T. Lauer, "A Practical Estimation Technique Using ERTS-1 Data," Ninth International Symposium on Remote Sensing of Environment, (April 15, 1974), pp. 32-33.

Haefner, Harold, "Snow Survey and Vegetation Growth in High Mountains (Swiss Alps)," (NASA-CR-131902; microfische E73-10586, 1973).

Hanson, David M., The Ecological Life Zones of Oregon: A Test of the Holdridge Model, (Masters Thesis, Oregon State University, December 16, 1974), pp. 39.

Ishaq, Achi M. and Dale D. Huff, "Application of Remote Sensing to the Location of Hydrologically Active (Source) Areas," Ninth International Symposium on Remote Sensing of Environment, (April 15, 1974), p. 69.

MacDonald, William R., "The Cartographic Application of ERTS/RBV Imagery in Polar Regions," (NASA-CR-132242; microfische E73-10651, 1973).

Martin, Kenneth R. and Frank Wobber, "Flooding Analysis by Satellite Imagery," Photographic Applications in Science Technology and Medicine, (July, 1974).

Meier, Mark F., "Evaluate ERTS Imagery for Mapping and Detection of Changes of Snow Cover on Land and on Glaciers," (NASA-CR-130313; microfische E73-10063, 1973).

5 _______, Evaluation of ERTS Imagery for Mapping and Detection of Changes of Snow Cover on Land and on Glaciers," NASA Symposium on Significant Results Obtained from the Earth Resources Technology Satellite - 1, (USGPO, Vol.1, Sec.B., 1973), pp. 863-875.

Morain, Stanley A., et. al., "Precipitation Pattern on ERTS-1 Image," (NASA-CR-133587; microfische E73-10930, 1973).

Mueller, Elizabeth L., Introduction to the Ecology of the Pumice Desert, Crater Lake National Park, Oregon (Masters Thesis - Purdue University, January, 1966), p. 110.

National Park Service, Crater Lake National Park Master Plan, (National Park Service, Dept. of the Interior, Crater Lake National Park, 1971).

3 National Weather Service, U.S. Department of Commerce - National Oceanic and Atmospheric Administration, Record of Climatological Observations, (National Park Service, Crater Lake National Park, Oregon, October 1973 - July 1974), pp. 10.

Nautical Almanac Office, The Nautical Almanac for the Year 1974, (Washington, D.C.: U.S. Naval Observatory, U.S. Government Printing Office, 1972), pp. 276.

Rose, Paul W., Geology Synopsis of Crater Lake National Park, (Unpublished but prepared for visitor distribution at Crater Lake National Park, May, 1974), pp. 14.

Salomonson, V.V., "Nimbus 3 and 4 Observations of Snow Cover and other Hydrological Features in the Western Himalayas," (Goddard Space Flight Center, 1973).

Schuman, Herbert H., "Hydrologic Applications of ERTS-1 Data Collection System in Central Arizona," NASA Symposium on Significant Results Obtained from the Earth Resources Technology Satellite - 1, (USGOP, Vol. 1, Sec.B., 1973), pp. 1213-1224.

[2]Sternes, G.L., Climate of Crater Lake National Park, (Oregon: Crater Lake Natural History Association, March, 1963), pp. 13.

Strahler, Arthur N., The Earth Sciences, (New York: Harper and Row, 1971), pp. 43-60.

U.S. Army Corps of Engineers, Snow Hydrology, (Portland, Oregon: North Pacific Division, Corps of Engineers, 1956), pp. 437.

Weigand, Craig L., "Reflectance of Vegetation, Soil and Water," (NASA-CR-12972, Microfische E72-10364, 1972).

Weller, Gunter E., "Survey of the Seasonal Snow Cover of Alaska," (NASA-CR-129658, Microfische E72-10344, 1972).

Wiesnet, D.R. and D.F. McGinnis, Jr., "Snow Extent Mapping and Lake Ice Studies Using ERTS-1 MSS Together with NOAA-2 VHRR," NASA Symposium on Significant Results Obtained from the Earth Resources Technology Satellite - 1, (USGOP, Vol.1, Sec.B., 1973), pp. 995-1009.

[1]Williams, Howel, "Crater Lake," (Denver, Colorado: U.S. Geological Survey, Department of the Interior, written description on the Crater Lake National Park and Vicinity, Oregon, topographic map, 1956).

Wobber, Frank J., "Facilitating the Exploitation of ERTS Imagery Using Snow Enhancement Techniques," (NASA-CR-133587; Microfische E73-10930, 1973).